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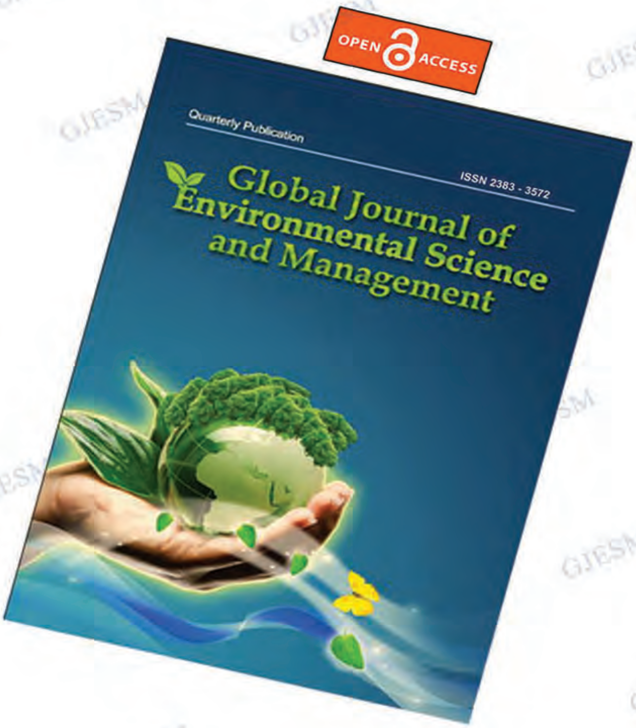

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SPECIAL ISSUE: Eco-friendly sustainable management
REVIEW PAPER

Environmental microbial communications in gram-positive and gram-negative bacteria

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ABSTRACT

Microorganisms are present in nature and shape an enormous a half of our micro- and macro-environment. Quorum sensing is the process of intercellular conversation that enables microbes to perceive their surroundings and change their behaviour, allowing them to remain like cellular organisms. Both Gram-positive and Gram-negative microorganisms use quorum sensing frame work for communicating with every other, though there may be distinct quorum sensing pathways available in Gram-positive and Gram-negative microorganisms. The scope of quorum sensing extends to inter-nation communication, mediate through numerous newly diagnosed extra-cell signal molecules known as autoinducers. The concentration of these signalling substances rises above a critical level when the population density does, causing particular gene expression patterns in the microorganisms. This may result in coordinated behaviours, including the development of biofilms, the generation of virulence factors, or other group activities. Without the ability to detect and react to the presence of their neighbours, microbial communities would not be able to adjust to changing environmental conditions or carry out collective actions that are essential for survival. Among those autoinducers, five major principal signal molecules are perturbed about side the classical quorum sensing system. The larger part of quorum sensing recognizing inhibitor takes bacterial quorum sensing share identifying as the even-handed and simply blocks the larger part recognizing plan of pathogenic organisms, which can demolish the pathogenicity of microorganisms without applying explicit squeezing factor, and doesn't execute the regular organisms or then again intrude with their standard physiological activities. To talk with each other, bacteria mix, release, and total minimal diffusible signal molecules, known as pheromones or autoinducers a pheromone (recognizing) depends upon its edge centre. Specific receptors found on the surface of the bacterial cell are required for the identification of pheromones or autoinducers. The proteins that can bind to diffusible signalling molecules often make up these receptors. These receptors bind to signalling molecules when their concentration rises over a predetermined threshold, setting off a signalling cascade that causes the bacteria to respond in concert. The prevailing article will speak about checking out basic variations between numerous quorum sensing systems in gram passitive and gram negative bacteria, and it is important to understand the communications of microorganisms in nature better. QS sensing will help as a regular language for signal communication of various microorganisms, yet the path where all proteins get the signals and turn on downstream sign transduction has changed phenomenally.

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INTRODUCTION

Microorganisms are free living or symbiotic and non-symbiotic present in the Environment. The microorganisms have built up a couple of correspondence stages inside cells to assist them with changing changes in their characteristic components (Barriuso *et al.,* 2018; Samimi and Shahriari Moghadam, 2020; Sivakumar *et al.,* 2022). Microorganisms have gotten a great deal of thought from specialists since they were predominantly found in the nineteenth century (Qu *et al.,* 2019; Iriany *et al.,* 2021). Such a correspondence between cells is called quorum sensing (QS) and offers perceiving, which relies on cell thickness and can a few attributes of microorganisms, for example, the arrangement of biofilm and the transmission of danger factors (Mehmood *et al.*, 2019). They are unavoidable and unflinchingly identified with individuals' bit by bit life, it covers a wide degree of hazardous and advantageous species, broadly related with science, food, bio security, medication, industry as well as, development, and so forth (Li *et al.,* 2020). Biofilms are formed by i) initial contact state in which pilli and flagella are helping the microbial cells to connect the surface through van der Waals force, adhesive process and cohesive process and the bond between the surfaces and microbial cells are increased by the strength of pilli and flagella, ii) microbial colony formation in which multiplication of microbial cells started after the stable attachment to the surface through chemical signalling and many types of microbial communities help to make microbial colony within the biofilm, iii) maturation state in which auto inducer signals are helping the microbial cells to communicate one another and gene products are generated that is used for formation of three dimensional biofilm, and (iv) detachment state in which saccharolytic enzymes are released within the microbial cells, which helps the surface of the biofilm to release the microbial cells and as well as the same to make new microbial colonialization in a suitable another surface (Paluch *et al.,* 2020). QS is one of the methods to measure a cell-to-cell correspondence which allows the microorganisms to share cell thickness and quality change data. QS is a reformist cycle that is completed between the limiting of an extracellular signature (autoinducer) and a particular receptor. The limiting of autoinducer to QS receptor prompts a change of gigantic worth clarification when the autoinducer fixation advancements to a critical fixation. From now on, this course various cycles like bioluminescence creation, biofilm development, optional metabolite creation, a limit concerning DNA take-up, and ruinous propensity factor creation. Autoinducers accumulate as the density of microbial cells in the biofilm increases (Yi and Dong, 2020). The QS stages in bacteria is shown in Fig. 1. A bigger part recognizing is a cell-to-cell correspondence measure that draws in organic entities to everything because of microbial cell wall thickness and surface area. The aims and knowledge gap of the current study are to know the gram positive and gram-negative bacterial communication with respect to biotic and abiotic stress. These knowledge gaps will be filled with an understanding of the biotic and abiotic stresses that the gram passitive and gram negative bacteira would communicate for nutrient availability and other microbial stress in the soil. This study was carried out at both the Amity Institute of Horticulture Studies and Research, Amity University, Uttar Pradesh, India, and the Kalasalingam Academy of Research and Education, Tamil Nadu, India, in 2023.

The Predominant part recognizing joins the creation, movement and collection wide affirmation of extracellular hailing molecules, which are called autoinducer. Autoinducers complete in the climate as bacterial population thickness increments. The QS cycles that are obliged by quorum recognizing, for example, bioluminescence, the transmission of ruinous inclination factors, creation of community things and biofilms arrangement that is insufficient and extreme due to involvement of introverted bacterial cell. The QS is fundamental for the independence of microorganisms since it grants them to endeavour a total lead to smooth out their chances even with instabilities in their present condition. QS insinuates an instrument of synchronization of value explanation as a segment of cell thickness and environmental conditions. QS is used as a wonder of cell correspondence in various marine tiny bacterial species, *Vibrio fischeri* and *Vibrio harveyi* (Papenfort *et al.,* 2016; Turan and Turgut, 2021). The larger part of QS recognizing inhibitor takes bacterial QS share identifying as the even-handed and simply blocks the larger part recognizing plan of pathogenic organisms, which can demolish the pathogenicity of microorganisms without applying explicit squeezing factor, and doesn't execute the regular organisms or

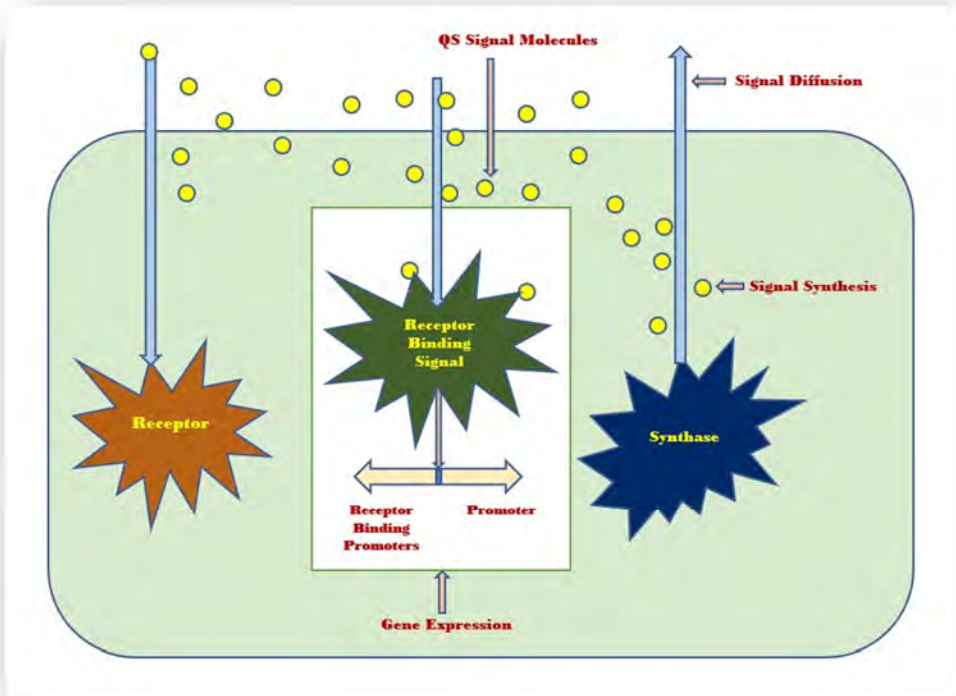

Fig. 1: QS stages in bacteria

then again intrude with their standard physiological activities. To talk with each other, bacteria mix, release, and total minimal diffusible signal molecules, known as pheromones or autoinducers a pheromone (recognizing) depends upon its edge centre. The response of microbes is provoked when a required concentration is reached. The QS coordinates the expression of different pathogenic characteristics (Kareb *et al.,* 2019). The microorganisms use QS to control various ranges of formation of virulence and biofilm. The QS inhibitors (QSIs) interfere with the QS signaling pathway through AI signaling molecules, receptors and downstream signaling cascades and suppress the formation of biofilm that control the microbial infections (Abbas *et al.,* 2020). As of now, three methods are customarily used to perceive QS share identifying signal particles namely, (i) biosensors are used to recognize AHLs, the signals of microbes in QS framework facilitates the flood of distinctive pathogenic attributes (Ohta *et al.,* 2020) and strains containing AHL strains could make the bacterial biosensors for phenotypic changes, (2) the plan of QS signalling identifying signal molecules could be recognized by chromatography through TLC and HPLC, and (3) the chromatography TLC combines with TLC-Biosensor to recognize greater part distinguishing signal particles (Li *et al.,* 2020). The QS framework is formed with the support of lux AB and lux CDE encoding proteins to produce the luciferase substrate that leads to bioluminescence. The numerous sorts of pathogenic microorganisms can adjust to various conditions directing the responsible qualities for biofilm creation, antibiotics, and exchange of genetic material during either transformation or formation. The majority of microbes are detecting the framework that depends on creation, delivery, and extracellular identification of signalling atoms, and auto inductors. These signals from the microbes are arriving at the appropriate limit concentration and cooperate with the receptor protein that promotes and facilitate the variations in the declaration of explicit qualities (Abisado *et al.,* 2018). Auto inductors in Gram-negative microscopic organisms are influenced by N-acylated homoserine

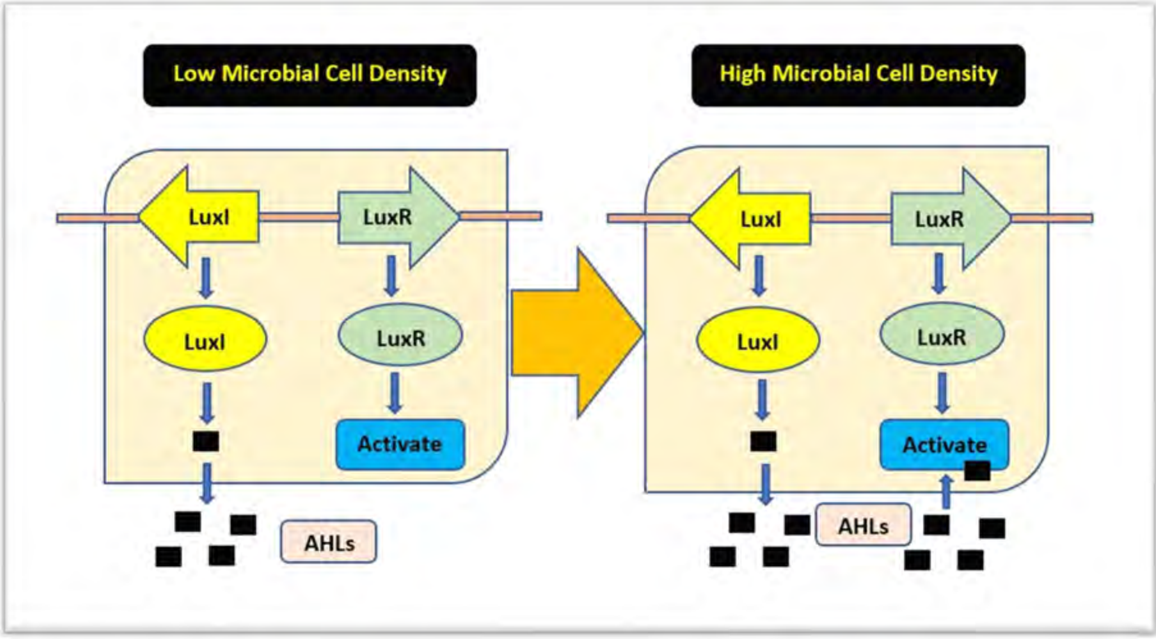

Fig. 2: Molecular mechanism of QS in gram positive bacteria

lactones (N-AHLs) and arranged by catalyst LuxI. The quantity of multiplying cells decides the thickness of the bacterial populace when N-AHLs and LuxI infiltrate into the microbial cells. While arriving at the appropriate edge fixation, the receptor protein LuxR is actuated and reached the highest targeted effector qualities. There are two sets of LuxI/LuxR homologs viz., LasI/LasR and RhlI/RhlR are developed in the QS framework of Gram-negative bacteria *Pseudomonas aeruginosa*. The QS framework controls the flow of numerous destructiveness factors like elastase, soluble phosphatase, protease, and exotoxin A. As well as, Gram-positive microbes utilize the short oligopeptide signals and split them into two-part. Gram-positive microbes reliably conveyed oligopeptides and two-region structures that incorporate kinase receptor sensor and cytoplasmic record discovery, which quickly changes quality explanation. The trademark pieces of greater part recognizing in Gram-positive microorganisms have been comprehensively investigated elsewhere (Paluch *et al.,* 2020). Molecular mechanism of QS in gram positive bacteria is shown in Fig. 2.

Both Gram-positive and Gram-negative microorganisms apply greater part recognizing for correspondence regardless, they produce different auto-inducers. The peptides have a gigantic hidden assortment and occasionally go through post-translational changes. Gram-negative microorganisms primarily depend upon N-AHL particles while Gram-positive infinitesimal organic entities use changed oligopeptides. A kind of autoinducers are boron-furan-derived signal iotas and perceived by Gram-positive and Gram-negative microorganisms (Verbeke and Craemer 2017). The important four fundamental features are found in known Gram-negative greater part identifying systems. Most importantly, the autoinducer structures are made with AHLs S-adenosylmethionine particles, which diffuse energetically through the bacterial layer. Autoinducers are restricted with inward layer and cytoplasm receptors. The dominant part is distinguishing consistently changes modest bunches to numerous characteristics that help diverse natural cycles. The autoinducer-driven authorization of QS is recognizing fortifies and the combination of the autoinducer activates a feed-forward circle that progresses the concurrent quality enunciation in the general population (Papenfort *et al.,* 2016). Gram-negative microorganisms use a couple of autoinducers that are uncovering the nuclear elements, which give the disposition receptors in the perceiving solid molecules. Greater part identifying information is often fused by little RNAs that regulate the target quality expression and work in input circles. Dominant part distinguishing network plans advance hailing fidelity, passing control, and versatile data yield components. Huge requests regarding greater part identifying are: the mystery do bacterial cells zero in on one autoinducer over another (Papenfort *et al.,* 2017). The kinase receptor moves phosphoryl social events for safeguarding the aspartate (formed during the amalgamation of any base and aspartic acid), which subsequently may be instituted. Gram-positive microorganisms use peptides as autoinducers for larger part recognition. Peptides joined with ribosomes as prototype peptides also, go through posttranslational changes and release to become incited and settled. At the point when everything is said in done, the release of the AIP is worked on by a film-related Adenosine triphosphate (ATP) confining tape (ABC) transporter. Autoinducing peptides (AIPs) accumulate as the general population thickness grows in the environment. AIP confines to receptors that begin the receptor kinase incitation by phosphorylation on an observed histidine development when reached a particular edge level. The response regulators impact the record of targeted AIP characteristics, receptor kinase characteristics, characteristics of the response regulator, and ABC transporter characteristics (Verbeke *et al.,* 2017). At present, the new developments of omic signs of progress, there stays to be an absence of data concerning microbial cell to cell correspondence in the rumen microbiome. During unadulterated culture examinations of non-ruminant origination viz., *V. fischeri*, *Vibrio harveyi*, Pseudomonas *aeruginosa*, and *Escherichia coli* revealed that the Gram-negative infinitesimal organic entities consistently use AHLs and Gram-positive infinitesimal creatures use furanosyl borate diester. In both Gram-positive and Gram-negative microbes, there is upregulation of QS autoinducer artificial materials, followed by receptor confining, and prompts variations in all things that are considered in microbial quality explanation as a result of extended destructiveness. These assessments design the microbial cell to cell correspondence and help the structural arrangement, regardless of their genuine nature of microbiome networks in the biofilms (Won *et al.,* 2020). The identified AHLs in a rumen fluid indicates the availability of the number and type of cell divisions in a rumen microbiome. The testing of unadulterated social orders alone may not recognize the type of microbes produced using AHLs in the Gram-negative bacteria including *Anaerovibrio lipoly*ticus 5S, *Fibrobacter succinogenes* S85, *Megasphaera elsdenii* LC1, *Prevotella brevis* GA33, *Prevotella bryantii* B14 etc., and Gram-positive microorganisms including *Butyrivibrio fibrisolvens*, *Lachnospira multiparus* 20, *Ruminococcus flavefaciens* and *Streptococcus bovis* YM150. As well as, it is to be noted that AHLs signal is lessened in the required rumen fluid, due to the microbiome changes (Won *et al.,* 2020).

Bacterial communication

QS microorganisms to team up or rival each other (inside a creature types and between species) by getting sorted out the announcement of totals and overseeing physiological activities. QS is a pattern of intercellular correspondence, being remarkably contrasted with other analyzed kinds of associations among bacterial organizations in an assortment of normal claims to fame (e.g., natural and land and water proficient) (Hmelo *et al.,* 2017). They fuse the creation of discretionary metabolites against microbial extracellular hydrolytic synthetic compounds, bioluminescence, exopolysaccharides sporulation, valuable cooperation, bacterial arrangement, release of ruinous tendency variables, biofilm improvement/detachment, and other natural practices. These metabolites are important for making the different colonization (Vadakkan, 2018). QS-set up coordinated efforts are dependent concerning the cell thickness and arise through the creation of autoinducers (AIs) signal synthase and the signal receptor (Papenfort *et al.,* 2015). During the bacterial turn of events, these hailing particles are continually made and conveyed into the overall environment until showing up at an edge center, in any case, called "dominant part level" (Hmelo *et al.,* 2017). The AIs are realized by express receptor proteins bound in either Gram-negative minuscule organic entities (cytoplasm) or Gram-positive microorganisms (biofilm) that create the QS-coordinated characteristics (Chen *et al.,* 2019). Regardless of the method of action used by helpful bacteria, the direct interaction between microorganisms and plant roots is the predominant step towards the plant's benefit. This is followed by the efficient colonisation of plant roots by bacteria. Active processes that significantly contribute to this process include chemotaxis and motility (Colin *et al.,* 2021). According to (De Weert *et al.,* 2002), the primary driver of competitive tomato root colonisation was Pseudomonas fluorescens WCS365's chemotaxis towards malic and citric acids in tomato root exudate. Bacteria typically reside as multicellular aggregates or biofilms in their natural habitats, where the cells are encased in a matrix of extracellular polymeric substances that are adhered to a surface. Bacteria are protected from unfavourable environmental conditions by living in biofilms. At the roots of plants, Pseudomonas bacteria build biofilms that act as a barrier to protect the roots from toxic chemicals or diseases as well as severe environmental factors like dryness and high temperatures. In this context, bacilli have received substantial study. Pseudomonas putida responds quickly to the presence of root exudates in soils, as demonstrated by (Espinosa-Urgel *et al.,* 2002), resulting in diverse root colonisation locations experiencing bacterial aggregation, and as a result so creating stable biofilms. In addition to being mobile, species also create biofilms (Jijón-Moreno *et al.,* In 2022) described the biological and advantageous consequences of two bacteria, Azospirillum oryzae NBT506, a Species that fix nitrogen as well as the PGPB Bacillus velezensis UTB96 were raised together. As the co-culture system demonstrated, Indole acetic acid (IAA) and a more stable biofilm were produced. Compared to monocultures, productivity was increased studies that directly see microorganisms attached to plants surfaces. As the climate changes and the Earth gets warmer, it becomes increasingly important for beneficial bacteria to function and survive in changing conditions. Isolated from plant growth-plant promoting (PGPB) bacteria in hot and dry climate zones, it is projected that plants or soils adapt faster than the plants in these environments to altering environmental circumstances environments. With the climate changing and the Earth getting warmer, it is imperative to test this idea. Beneficial bacteria must be able to function and thrive in a variety of situations. It is projected that PGPB bacteria solated from plants or soils in hot, dry climate zones will adapt to changing conditions more quickly than the plants that already exist in these habitats used cultivation-dependent techniques to extract bacteria from the Negev desert concerning to test this theory in an Israel (Khan *et al.,* 2018). Numerous bacterial varieties were discovered and examined on corn in small-scale field and greenhouse research. In contrast to untreated controls, one uncommon abiotic stress tolerant strain, Dietzia cinnamea 55, greatly improved the overall plant health of maize. Kumar and Gera (2014) previously reported that Brevundimonas sp. MDB4, which was discovered in a soil sample from the rhizosphere of growing sugarcane in a dry area of India also encouraged plant growth. Testing revealed that the bacterial isolate was multi-trait. PGPR that not only dramatically increased biological nitrogen fixation increase the growth of RCH 134-variety Bt cotton. Several studies support bacteria's capacity to aid stressed plants in growing surroundings to their capacity for lowering "stress" levels by "ethylene (Dhayalan and Karuppasamy, 2021). In semi-arid and dry areas, the consequences are more noticeable (Hassani *et al.,* 2021). On the other hand, halophytic plants and their related Microbiomes can shed light on the potential for crop growth. For instance, the halophyte Suaeda salsa's microbiota, demonstrating that the interior root tissues and rhizosphere of S. salsa are more abundant with bacteria that produce genes related to salt stress tolerance. Salt-tolerant bacteria were also identified from the It has been demonstrated that halophytes' rhizospheres increase salinity. Alfalfa, wheat, and other agricultural crops are under stress (Kearl *et al.,* 2019) as well as maize (Sorty *et al.,* 2016).

Gram-negative AHL bacteria communication

A distinctive CAI-1 is made by the essential ordinariness of homologs of CqsA in *Vibrio* species. The CAI-1 is a vibrio because *Vibrio* spp. has different affinities to CAI-1. AIs are iotas that are organized by the substrate called S-adenosylmethionine (SAM). The perceived class of AIs is AHLs that have N-AHL ring and 4–18 carbon acyl chain. LuxI-type impetuses have dominated in sole producer of

AHLs. The distinct nature of LuxM of LuxI can make intra-species correspondence of AHLs. Infinitesimal life forms species could be used the SAM signals for their species identification. The particles of diffusible signals factor (DSF) are combined by RpfF proteins in *P. aeruginosa* and *B. cenocepacia* (Ryan *et al.,* 2015). Both Gram-positive and Gram-negative microbes use the QS to communicate between the cells. Different pathways in both types of microbes may have different unique characteristic positions (Papenfort and Bassler, 2016). Without LuxI synthases, they recognize particular AHL particles made by various microbial species, consequently facilitating between microbial species correspondence (Hudaiberdiev *et al.,* 2015). The QscR in *P. aeruginosa*, and SdiA in *Escherichia* could be responded to mammalian molecules production**.** The LuxR bound with DNA to form stable LuxR-AHL buildings and LuxR proteins unbound with DNA are immediately tainted and AIs also bounded to either unequivocal layer receptors or cytoplasmic proteins (Papenfort and Bassler, 2016). The combination of LuxR/LuxI-type microbial structures, together with LasR/LasI and RhlR/RhlI in Pseudomonas aeruginosa facilitate between the cell correspondence (Papenfort and Bassler, 2016). The previous studies also confirmed the relationship between LuxR proteins with LuxR solo receptor and transient LuxR (Wu *et al.,* 2021). The joined receptors fill in as record factors to direct handfuls to many qualities that influence biofilm arrangement, harmfulness, and other natural cycles in microorganisms. QS particle receptors set up a feed-forward circle when managing qualities articulation, which is called autoinduction. This system builds the autoinducers combination, thusly advancing coordinated qualities articulation in the populace (Papenfort and Bassler, 2016). The two Las and Rhl frameworks may control the own LasI and RhlI qualities and LasI/LasR framework can direct the RhlI/RhlR framework. In Pseudomonas aeruginosa, there exists a more mind-boggling majority detecting administrative framework organization, which is made out of las framework, Rhl framework and quinolone signal framework, and every framework is interconnected (Gokalsin *et al.,* 2017) autoinducers OdDHL and BHL are orchestrated by LasI and RhlI synthetases in the RhlI/RhlR and LasI/LasR frameworks (Kariminik *et al.,* 2017). The components of acyl homoserine lactone (AHL) are a lactone ring and a side chain with carbon atoms that are between C8 and C14 in length. They are mostly found in Gram-negative microorganisms and are used for intraspecies communication. As well as, the homoserine lactone moiety is provided by a collection of homologous LuxI (AHL synthase) proteins, which use S-adenosyl methionine as a building component. Low concentrations of LuxI are formed at low cell density, which is followed by the creation of AHLs at low concentrations that can freely pass across the cell membrane. Up until the threshold level at which the transcriptional activation protein LuxR (the AHL receptor) binds to the AHL molecules, AHLs accumulate with bacterial growth (Prazdnova *et al.,* 2022). After forming dimers or multimers, the AHL-LuxR complex binds to its specific promotor and promotes the production of bacterial genes relevant to QS (Boo *et al.,* 2021; Rutherford *et al.,* 2012; Scutera *et al.,* 2014; Steindler *et al.,* 2007). The majority of AHL biosensors use the following topologies to identify QS gene networks: A reporter gene expressed by the homologous promoter homolog of the LuxR, and (a) a QS transcription activator expressed by an induced or constitutive promoter. Furanosyl borate diester and 4, 5-dihydroxy-2, 3-pentane dione (DPD) derivatives make up uto-inducers-2 (AI-2). It is produced intraspecies and is present in both Gram-negative and Gram-positive bacteria. It is also considered to be the most common signalling molecule (Okada *et al.,* 2005). Although the exact mechanism of action of AI-2 is yet unknown, it is known that the phosphoenolpyruvate phosphotransferase system activates the LsR transport system (Pereira *et al.,* 2012). The bioluminescent system of the marine bacterium Vibrio harveyi was the predominant place where AI-2 was discovered. It is made up of two complex components, one of which is catalysed by the luxS gene locus and related homologs and the other by the S-adenosyl homocysteine nucleosidase enzyme. AI-2 controls a variety of bacterial species' behaviours, including the development of biofilms in Salmonella Typhimurium, Streptococcus mutans, and V. cholerae (Yoshida *et al.,* 2005). As well as, they control the motility of Campylobacter jejuni and E. coli (Girón *et al.,* 2002; Sperandio *et al.,* 2001) Numerous bacterial traits, including Bacillus anthracis growth, V. cholerae pathogenicity, and V. harveyi bioluminescence, can be controlled by

Table. 1: List of AHL gram negative bacteria's communication system

Name of the gram -negative bacteria	Control structure	Soureces
Aeromonas hydrophila	AhyI/AhyR	Koul *et al.*, 2015
Aeromonas salmonicida	AsaI/AsaR	Schwenteit *et al.*, 2011
Erwinia stewartii	EsaI/EsaR	Ramachandran *et al.*, 2013
Escherichia coli	LsrK/SdiA	Machado *et al.*, 2019
Pseudomonas aureofaciens	PhzI/PhzRTraI/TraR	Peng *et al.*, 2018
Pseudomonas aeruginosa	LasI/LasRRhlI/RhlR	Mukherjee *et al.*, 2019
Ralstonia solanacearum	PhcB/PhcR	Mori *et al.*, 2018
Rhizobium etli	RaiI/RaiR	Dixit *et al.*, 2017
Salmonella Typhimurium	LsrK/SdiA	Liao *et al.*, 2019
Vibrio anguillarum	VanI/VanR	Liu *et al.*, 2018
Vibrio harveyi	LuxM/LuxN	Mukherjee and Bassler, 2019

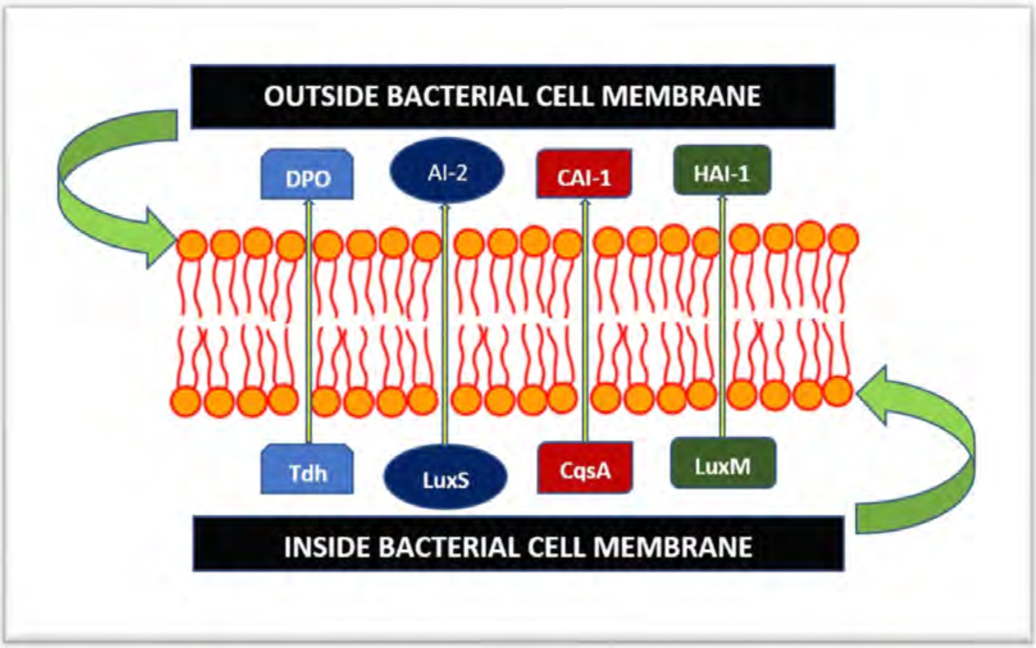

Fig. 3: Gene expression mechanisms in *V. harveyl* with four different autoinducers

conjugating AI-2 with AIPs and AHLs (Zohar *et al.*, 2015). The List of AHL Gram negative bacteria's communication system is presented in Table 1.

The pharmaceutical quality system (PQS) has a spot with the combination of 2-alkyl-4-quinolone and 2-heptyl-4-quinolone, and the same contributes to the encoded synthases in the operon phnAB, pqsABCD and pqsH. The two autoinducers are instigated harmful components. The Las and Rhl of PQS studies revealed that Las's system theatres a positive authoritative work by determinedly overseeing PqsA, PqsH, and PqsR, and PQS quality mix is conversely overseen through Rhl structure (Heeb *et al.*, 2011). Gene expression mechanisms in *V. harveyl* with four different autoinducers is shown in Fig. 3.

Gram-positive AIP bacteria communication

The typical features of QS circuits indicated the various capabilities among Gram positive and Gram negative infinitesimal organic entities. The AIs in various Gram positive infinitesimal organic entities are oligopeptides. The AIP is encoded as a forerunner

Table 2: List of different QS bacterial receptors

Different Receptor's	Signal molecule	Intraspecies or interspecies	Representative receptors	Bacteria
Typical LuxR type	AHLs	Intraspecies	LuxR	*Vibrio fischeri*
LuxR solo type	AHLs	Intraspecies	SdiA	*Escherichia coli*
Gram-negative two-component type	HAI-1	Intraspecies	LuxN	*Vibrio harveyi*
Gram-positive two-component type	AIPs	Intraspecies	ArgC	*Staphylococcus aureus*
Gram-positive RRNPP-type receptors	AIPs	Intraspecies	Rap	*Bacillus subtilis*
Gram-positive RRNPP-type receptors	AIPs	Intraspecies	Rgg	*Streptococcus thermophiles*
Gram-positive RRNPP-type receptors	AIPs	Intraspecies	NprR	*Bacillus cereus*
Gram-positive RRNPP-type receptors	AIPs	Intraspecies	PrgX	*Enterococcus faecalis*
Gram-positive RRNPP-type receptors	AIPs	Intraspecies	PlcR	*Bacillus thuringiensis*
AI-2 receptors	AI-2	Interspecies	LuxP	*Bacillus thuringiensis*
AI-2 receptors	AI-2	Interspecies	LrsB	*Salmonella typhimurium*
AI-3 receptors	AI-3/epinephrine /norepinephrine	Interspecies	QseC	*Enterohemorrhagic Escherichia coli*

from QS operon to form authorized AIP-QS, by then arranged and released extracellular by explicit transporters. The authorized AIPs produced straight and cyclized type of amino acids. The flexible nature of AIPs is coevolved with their receptors in *S. aureus*. Noncognate AIPs inhibitory influence the QS in various strains but allows only one strain to mature its definite strength. The sensor kinases auto-phosphorylate resulting to limiting to AIPs, in addition, the phosphoryl pack is connected a cytoplasmic protein, which manages the affirmation of QS frame work characteristics. The Agr structure of *Streptococcus aureus*, and Fsr structure of *Enterococcus faecalis* seal in AIP receptors (Zschiedrich *et al.,* 2016; Ali *et al.,* 2017). A secretory system in the pre-AIPs of AIP-QS circuits is transmitted by extracellular proteases for instance, transmitted unprejudiced protease B (NprB). The imported AIPs are continuing to tie the segments for controlling the DNA verbalization with the oligopeptide permease structure. The delineation of typical QS system is controlled by the PapR-PlcR system in *Bacillus cereus* (Pomerantsev *et al.,* 2009). The QS operon autoinduction encodes the pre-AIPs, receptors, transporters, proteases, and controllers to synchronize QS response (Pomerantsev *et al.,* 2009).

Bacterial AI-2 species correspondence

Tiny life forms direct their actions by recognizing the environment. Yet countless above AIs are significantly expressed as being made and seen by a lone creature gathering, new assessments show that a couple of particles can enable species correspondence. QS -subordinate characteristics of shine in *V. harveyi* stains could be started by supernatant sans cell from a couple of arbitrary bacterial creature gatherings. The appearance of the sanctioned methyl pack between SAM and particle acceptors bounces increase to S-adenosylhomocysteine and changed to S-ribosylhomocysterine (SRH) by the protein S-adenosylhomocysteine nucleosidase. LuxS is generally used to isolate the SRH that make a flimsy temporary 4,5-dihydroxy-2,3-pentanedione (DPD), then it may steeply cyclize to gather of dynamic computerized reasoning 2 hailing molecules and released by exporters (Pereira *et al.,* 2013). The receptor LuxP found in the periplsmic protein of *Vibrionales* may team up with LuxQ to form a two-section of LuxPQ authoritative structure. In addition, a boron bounded AI-2 and LuxP prompts the LuxQ auto-phosphorylation and describe the QS frame work characteristics. The high affinity periplasmic protein

LsrB receptor is presented in *S. typhimurium*, *B. cereus* and *E. coli* species. The non-borated LsrB receptor was masked by a transporter of LsrA, LsrC, and LsrD. The phosphor AI-2 (Table 2) is phosphorylated by LsrK kinase, which connects further to LsrR and amplify the progress of Lsr structure. The one of AI-2 receptor RbsB is found to have over 70% homology character with the periplasmic ribose ABC transporter in *Escherichia coli*. The shortfall of pearl developments of RbsB structure confining to AI-2 are foggy (Armbruster *et al.,* 2011). Because it lacks the luxS gene, Pseudomonas aeruginosa cannot manufacture the AI-2 signalling molecule. The las, rhl, pqs, and iqs QS systems are used by P. aeruginosa to control the synthesis of various virulence factors and biofilms, which causes tissue damage and inflammation, impairing the immune system in an infected person (Van Delden and Iglewski, 1998). As a result, research on QS inhibitors (QSIs) that target QS mediated by acyl-homoserine lactone (AHL) signalling molecules has been concentrated on P. aeruginosa (Chbib *et al.,* 2020; Jiang *et al.,* 2020). Nevertheless, P. aeruginosa is able to detect the AI-2 signalling molecule produced by other bacteria, including Escherichia coli, Salmonella typhimurium, Streptococcus mitis, and Staphylococcus aureus (Hotterbeekx *et al.,* 2017). According to recent research, C1-alkyl AI-2 analogues decreased the bioluminescence associated with V. harveyi QS (Lowery *et al.,* 2009), and analogues of the precursor compound for the AI-2 signalling molecule, 4,5-dihydroxy-2,3-pentanedione (DPD), such as butyl and pentyl-DPD, were found to significantly reduce the production of pyocyanin by P. A novel method of treating P. aeruginosa and S. aureus-related bacterial infections involves inhibiting the AI-2 QS system with a QSI. List of different QS Bacterial Receptors is presented in Table 2.

Intraspecific bacterial communication

LuxR-type protein in the Gram-negative microbes and RRNPP-type protein in the Gram-positive microbes go probably as their QS receptors through transmembrane two-section histidine sensor kinases. Las and Rhl structures of Pseudomonas aeruginosa was investigated vigorously as Pseudomonas quinolone hailing, where PqsR protein is used as receptor. The molecules 3-hydroxymethyl myristate (3-OH-MAME) and 3-hydroxy palmitate (3-OH-PAME) are the unsaturated fat subordinates in QS frame work system (Hikichi *et al.,* 2017). The network was formed by receptor PqsE and synthase RhlR, in the QS system of *P. aeruginosa* (Mukherjee *et al.,* 2018). The 3-OH-MAME and 3-OH-PAME are mixed with methyltransferase PhcB to form the histidine kinase PhcS receptor (Ujita *et al.,* 2019). Notwithstanding AHL mediated QS structure is found in Phc type QS system of *Ralstonia solanacearum* (Cornelis, 2020) and bounded with two hailing iotas PhcR and PhcA to direct the virulence. As well as, the sliding transmission of Phc type QS system signals is having two-section structure (Yi *et al.,* 2020).

AI3 signal creation

Researchers have as well as, cleaned a reputed autoinducer signal, and computerized reasoning 3, from the receptors luxS/AI-2 in the microbes *E. coli*. Previous investigiations also proved that Computerized reasoning 3 mix is a self-sufficient of LuxS. As well as, resources the host synthetic substances epinephrine (Epi)/norepinephrine (NE). A later report exhibits that AI-3 are a couple of things which have a spot with the pyrazinone family. The threonine dehydrogenase (Tdh) interceded AI3 signal creation and aminoacyl-tRNA synthetases related unconstrained cyclization are two central reactions among various reactions occurred in the microbes (Kim *et al.,* 2020).

Indole based bacterial communication

Without the essential for unequivocal receptor confining, indole particles can order succinate related characteristics, or circle back to managerial proteins with various normal limits like biofilm plan, hurtfulness, plasmid security and drug resistance. Indole manages the RamA transcriptional regulator and it is used for assembling the drug resistance in the non-indole making species *S. enterica* and tie the pyruvate kinase *S. aurantiaca*. Previous researchers are concentrated on effect of indole on biofilm of various microbes particularly on *E. coli* strains. The Indole creation in cells shows up at a generally outrageous and is consistently kept up in the fixed stage. Microorganisms are essential for the meting out of specific enrichments in amino acids and starches. Despite the relationship of microorganisms decided metabolites in rule of have physiology and the resistant structure, best in class confirmation indicates that they might work as a strategy for correspondence, which impacts the bacterial lead accordingly. Indole is an ordinary model, which may influence the indole-conveying activities and non-indole-making organisms in a surprising manner. Indole is completed during tryptophan is defiled through tryptophanase (TnaA) and yields an essential outcome on this cooperation as well as, the Tna operon interprets the TnaA and TnaB that are helpful for tryptophan take-up normally. The concentration of extracellular indole is affected by glucose, temperature and pH (Kim *et al.,* 2015).

Autoinducer 2 (AI-2) communication

The bioluminescence is controlled by the LuxO transcriptional regulator (phosphorylates). Through intra-species correspondence instruments, it is presently grounded that microorganisms can sort out their lead in more complicated conditions. The AI-2 is a borate farnesyl diester receptors that communicate between Gram-negative and Gram-positive microorganisms. Man-made insight 2 is normally perceived in comparing through a QS framework incited by either AHL or AIP autoinducers. Despite it seeing through acylated homoserine lactone (HSL) autoinducers (AI-1), the microbes *V. harveyi* could pass on with various species through AI-2. The LuxS impetus yields AI-2 and it is distinguished via a periplasmic LuxP protein. The LuxQ protein kinase combines with AI-2/LuxP to produce LuxU (phosphotransferase). This wonder can be found in equivalent and / or on the other hand concurrently with the acknowledgment of either AHLs or AIPs. *V. harveyi* are identified in pathogenic organisms by hybrid QS circuits. The LuxS/AI-2 structure in the microbes *Listeria monocytogenes*, *Escherichia coli*, and *Staphylococcus aureus* are used to control the biofilm plan (Gonzalez *et al.,* 2006). Nonetheless, this component isn't simply limited to pathogenic microbes. It is likewise seen in lactic corrosive microscopic organisms. The genomic examination by the previous researchers revealed that the LuxS quality homologs are presented in *Lactobacilli*. As well as, autoinducer 3 (AI-3) is especially intriguing to clarify between prokaryote and eukaryote genera communication. The LuxS is engaged by the development and capacity to frame biofilms in *Lactobacillus rhamnosus* (Brink and Nicol, 2014). Simulated intelligence 2 pheromone is also included in the *L. lactis* to form the brutal conditions of the human stomach related plot. The QS pathway including AI-2 QS pathway is actuated in *L. acidophilus* by monocytogenes. The LuxS quality is especially existing in *Lactobacillus plantarum* and is believed to engage with bacteriocins biosynthesis. For sure, the digestive system is a perplexing environment that has numerous bacterial species that likely exist together by interspecies QS framework. Computer based intelligence 3 is created by commensal bacteria although what's more by various microorganisms like *E. coli*. The AI-3 impels the pathogenic characteristics and contaminates the QS frame work (Kareb *et al.,* 2019).

Different groups of QS receptors

LuxR-type receptor

Presently, LuxR receptors in Gram-negative microbes could be divided into LuxR receptor and LuxR Orphan, which perceive acylhomoserine lactones (AHLs) through LuxI synthase. The LuxR protein in *V. fischeri* detects and ties the AHLs and LuxI proteins to form the luxICDABE (luciferase operon). As of now, in the QS site, huge number of AHLs and LuxR receptors have been briefed (Rajput and Kumar 2017). Different other gram-negative minute natural elements have been identified to utilize and organize their QS model. The regular LuxR-type receptors and new standard LuxR receptors are presented Tables 3 and 4. The TraR was discovered to be resistant against proteases in collapsing of 3-oxo-C8 HSL (3OC8HSL). The TarI and TraR are effectively annihilated by proteolysis without 3OC8HSL. The TraR in the *Agrobacterium tumefaciens* manages the qualities of replication and formation of the tumor actuating plasmid. The symmetric homodimer TraR protein has 3OC8HSL and C-terminal DNA restricting space and TraR is also supposed naturally unstructured protein. The SinR and ExpR receptors hinder the outflow of SinI and ExpR managed the the declaration of SinR and ExpR at the high AHLs. The TraR2 and QS-2 receptor perceives 3OC8HSL and successfully endorses Tra box DNA (Wang *et al.,* 2014). The QS framework influences the regulation of Ti plasmid reproduction and restricting. SinO rhizobium as well as, has TraI-TraR framework along with SinI-SinR. The characteristics of TraI-TraR framework is similar to the characteristics of LuxI-LuxR framework. The component in the SinI-SinR framework has both positive and negative administrative criticism system and SinR articulation is improved at low AHL levels.

Table 3: Different bacterial LuxR/Typical LuxR signalling molecules

Name of the Bacteria	LuxR/Typical LuxR	Signaling molecule	Sources
Agrobacterium tumefaciens	TraR; TraR2	3OC8HSL	Wang *et al.,* 2014
Sinorhizobium fredi	TraR; SinR	Short-chain AHLs; long-chain AHLs	Acosta-Jurado *et al.*, 2020
Pseudomonas putida	PpuR	AHLs	Kato *et al.,* 2015
Acinetobacter baumannii	AbaR	3-Hydroxy-C12-HSL	Niu *et al.,* 2008
Erwinia carotovora	ExpR	3-Oxo-C6-HL	Cui *et al.,* 2006
Serratia marcescens	SpnR	C6HSL	Takayama and Kato, 2016
Rhodopseudomonas palustris	RpaR	pC-HSL	Hirakawa *et al.,* 2011

Table 4: Different bacterial LuxR/LuxR solo signalling molecules

Name of the Bacteria	LuxR/ LuxR solos	Signaling molecule	Sources
Vibrio cholera	VqmA	DPO	Papenfort *et al.,* 2015
Photorhabdus asymbiotica	PauR	Dialkylresorcinols (DARs)/cyclohexanediones (CHDs)	Brameyer *et al.,* 2015
Photorhabdus luminescens	PluR	Photopyrones (PPYs)	Brachmann *et al.,* 2013
Pseudomonas fluorescens	PsoR	Plant signal molecule	Subramoni *et al.,* 2011
Pseudomonas sp. GM79	PipR	Plant signal molecule	Coutinho *et al.,* 2018
Xanthomonas oryzae pv. Oryzicola	XocR	Not yet determined	Xu *et al.,* 2015

The motility, development of biofilms and plasmids are accomplished by the QS framework in the microbes *S. fredii* HH103. Although, the physiological attributes in the *S. fredii* HH103 (the creation of EPS what's more, the inactivation of surface movement) are controlled by other flagging atoms, for example, flavonoids and NodD1 (Acosta-Jurado *et al.,* 2020). Different bacterial LuxR/Typical LuxR signalling molecules and different bacterial luxr/luxr solo signalling molecules is presented in Tables 3 and 4.

Two-portion bacterial film QS

Despite the LuxR type QS, some of the Gram-negative microorganism's viz., *Vibrio harveyi* and *Vibrio cholerae* have two partition biofilms. In *V. harveyi*, LuxN, LuxPQ and CqsS receptors have been recognized as two-section film bound with QS receptors. Whereas, in *V. cholerae*, LuxPQ, CqsR CqsS, and VpsS was documented as two-section film bound QS receptors. At high cell densities, dephosphorylation of LuxU and LuxO, and dephosphorylated LuxO are not activating Qrr sRNA quality, yields there is a reduced AphA, HapR/LuxR production (Rutherford *et al.,* 2011). The kinase of CqsR and VpsS is not obliged through CAI and AI-2 and jumbled independently with CqsR and VpsS signals. The kinase goes through autophosphorylation in low cell densities trailed by LuxU and LuxO phosphorylation. The phosphorylated LuxO starts recording the encoding characteristics of authoritative little ribonucleic acids (RNAs) and transcriptional institution of Qrr sRNA (Shao and Bassler, 2012).

Gram-positive bacteria QS receptors

The Gram-positive QS receptors are basically cytoplasmic receptors having bound sensor kinases, short unmodified peptides and long changed peptides (Neiditch *et al.,* 2017). The Rgg, Rap, NprR, PlcR and PrgX of RRNPP family are also the cytoplasmic receptors in the Gram-positive QS microorganisms. As of now, ComP in ComQXP receptor is also presented in the film bound sensor kinases.

Rgg/Rap/NprR/PlcR/PrgX receptors (RRNPP)

The Rap protein in the RRNPP family receptor is an inescapable in *Bacillus subtilis* included basic capacity and sporulation capacity as that of creation of either protease or exchange of ICES1 through constrictive and directive components. The different capacities of Rap proteins RapA/B/E/H/J and RapP/60 as negative receptors in the phosphorylation signal transduction framework regulators advance the regulation of Spo0F~P dephosphorylation that may restrain the spore development. Similarly, the record inhibitors Rap proteins (RapC/D/F/K/G/H and Rap60) tweaks hereditary capacity of *Bacillus subtilis* by debilitating capability of protein ComA. The Rap protein RapG controls the reaction rate in the modified DegU advertiser (Neiditch *et al.,* 2017). The previous study revealed that *B. subtilis* only produces 16 Rap proteins and the capacity of Rap protein family is not clear yet (Verdugo-Fuentes *et al.,* 2020). The Rgg type of protein in the RRNPP family stays a dimer in the ligand-bound construction and the NprR protein of RRNPP ought to be oligomeric, which varied from a dimer to a tetramer. At present, there are four types of Rgg proteins viz., Rgg1, Rgg2, Rgg3 and ComR are discovered. In *S. pyogenes* microorganism, the protein RopB is provoked by SIP signal that are affected by pH. The pH-fragile framework is bound by a SIP-fragile histidine shift, which are organized at the lower portion of the SIP pocket of RopB. The Rgg2 and Rgg3 proteins re-joined to peptide pheromones SHP2 and SHP3 and the same is used for the improvement in biofilm development, and tissue interruption in the *Streptococcus* microbes (Wang *et al.,* 2020; Do *et al.,* 2019).

Interspecific bacterial communication

AI-2 receptors

The periplasmic limiting protein LuxP is characterized predominent in *V. harveyi*. The receptor LsrB is noteworthy for massive assembly of periplasmic proteins, which are predominent found in *S. typhimurium*. The proteins LuxP and LsrB have a spot with the gathering of proclivity substrate limiting proteins. The periplasmic limiting protein LuxP bounded to (2S, 4S)-2-methyl-2,3,3,4-tetrahydroxytetrahydrofuranborate and LsrB bounded to (2R,4S)-2-methyl-2,3,3,4-tetrahydroxytetrahydrofuran (Miranda *et al.,* 2019). Until this point, two sorts of AI-2 receptors have been perceived: LuxP, LsrB. As well as, unusual LsrB in extension, ID of new receptor AI-2 could be cultured by screening genetically, which further isolates monstrosities from AI-2. The previous study revealed that the use of progression assessment and essential assumption could be perceived in AI-2 receptors. The other study indicated the strategy for perceiving dark AI-2 receptor against biotin neutralizer (Miranda *et al.,* 2019). The biofilm receptor LuxPQ is formed with histidine sensor kinase (LuxQ) and periplasmic confining protein (LuxP). The LuxPQ biofilm receptor in the QS frame work is transported in a piece of two-fragment Gram-negative QS receptor and arranged outpouring of QS-subordinate characteristics through Ais solidfication. The LuxP has expected to interact with 4-oxodocosahexaenoic destructive molecule in *Vibriosis* (Low *et al.,* 2019).

AI-3 receptors

Amino destructive gathering examination exhibited that QseC sensors were found in *Shigella*, *Salmonella*, and *Yersinia* species. The histidine sensor LuxPQ is a major biofilm receptor, found in both QseBC and QseEF two-section regulatory system (Creon, 2018). The QseC sensor associations with AI-3 to produce autophosphorylate, and QseB sensor associations with AI-3 to produce phosphorylates. As similar to adrenaline and norepinephrine, the QseC sensor responded to AI-3 receptor and indicated that QseC is major for gut verdure and the host correspondence (Bearson, *et al*., 2010). Both alphaadrenergic adversaries and QseC inhibitors could be effectively disturbed the QseC response and control destructiveness of the intestinal pathogenic greenery. Subsequently, QseC hailing is a capable framework for monitoring the microbiota infections. The QseEF is scattered than the QseBC in the intestinal microorganisms and QseEF is triggered predominent after QseBC is on track. The current investigations showed that the QseBC activity is constrained by QseG, and QseBC activity is also less obstructed by both epinephrine and norepinephrine signals. Plan and produced pathway of AI-3 have not been depicted since AI-3 substrate is made by Tdh and tRNA synthetases (Kim *et al.,* 2020).

LuxR solo sort receptors

The solo sort LuxR is also part of the QS frame work as that of fundamental LuxR receptor. The solo sort LuxR has no going with LuxI synthase; although, it could be directed the organisms to acclimate, which are confining to either AHLs or non-AHLs receptors (Nyffeler, *et al*., 2022). The previous studies indicated that 76% of LuxR proteins or LuxR solo proteins that

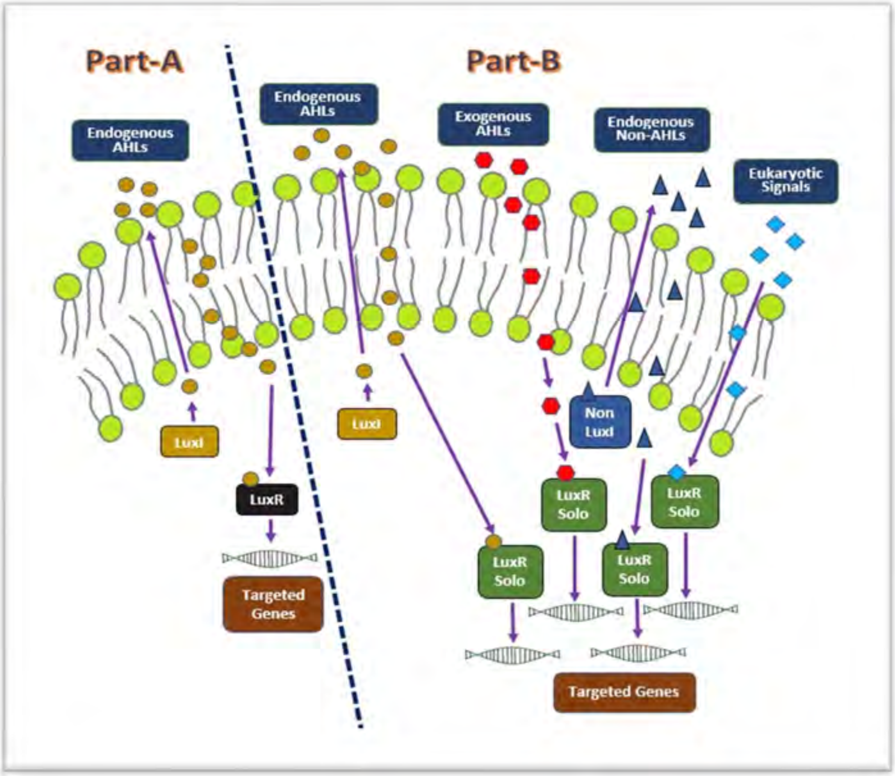

Fig. 4: LuxR and LuxR solo receptors in gram negative bacteria (Part-A: LuxR receptor binding with endogenous AHLs and part-B: LuxR solo receptor binding with endogenous AHLs)

are striking QscR in *P. aeruginosa*, CviR in *C. violaceum*, and SdiA in *E. coli*. QscR and SdiA may identify the AHLs of bacterial species. The characteristic of LuxR solo is representing the characteristic of VqmA and SdiA receptors VqmA and SdiA receptors. Fig. 4 indicates the LuxR and LuxR solo receptors in Gram negative bacteria (Hudaiberdiev *et al.,* 2015).

Activities of QS

By and large, greater part distinguishing was portrayed as cell–cell correspondence among minuscule organic entities, which results in record factor activity deviations, and as a result, there may quality explanation change. QS share identifying facilitated rehearses were portrayed as those that require the aggregate of the microorganisms in the people to go about as one to make the practices successful. As well as, biofilms and damaging tendency are acknowledged responsible to stream, AI-2 receptor is essential for microbial biofilms formation and dental plaque change. The new investigation grows these definitions by appearing between domain communication, responses by intracellular little iota compound signals. The Quorum recognizing has for a long while been recognized to achieve the formation of hazard issues and the biofilm plans**.** In other biofilm networks, QS share identifying propels contention, at any rate among non-family. For example, in *V. cholerae*, greater part recognizing starts type VI release, causing lysis of connecting non-family cells. The heterogeneity in quality enunciation that is compelled by greater part sensing (Grote *et al.,* 2015). The gut commensal bacterium *Blautia obeum* limits the damaging tendency of *V. cholerae* that is critical in retrieval from cholera. In the gut, AI-2 hailing has been actually uncovered for improving Firmicutes against Bacteroidetes through enemy of disease treatment and QS frame work shapes the microbiota composition in any occasion (Thompson *et al.,* 2015). The identifying pathways advance the synchronization of value enunciation among all bundle people. This phenotypic heterogeneity is seen as a critical best-supporting framework. Dominant part identifying determined heterogeneity moved comprehensively in *V. harveyi* and could be credited to status of LuxO phosphorylation and could be used for biofilms improvement in the microbes. Independent person cells have as well as, been represented in other systems; in any case, generally speaking, the sub-nuclear mechanisms, which underlie heterogeneity. Previous studies on *P. putida* suggested that AIs could be a heterogonous in young biofilms and AIs could also be triggered self-selection of QS frame work in individual cells, which showed that the natural limit of a larger part distinguishing sign can vary depending on the advancement conditions (Papenfort *et al.,* 2016).

FUTURE ASPECTS OF MICROBIAL COMMUNICATION

At present, the QS structure is an enormous examination space of income in the field of microbiology. Different fields of microbiology like soil, food and pathogenic microorganisms, which gained various levels of improvement in the evaluation of QS frameworks (Charousová *et al*., 2015; Macfarlane-Smith, *et al*., 2016). Although, different microbial combination fields examination is unique, the assessment dependent upon QS structure. Thinking about the outcomes of current assessment of piece of QS framework, it may manage organic issues like sewage treatment, compost degradation and expulsion of unsafe and risky sections; address recent concerns, for example, food dealing with and shielding; considering the piece of QS framework in pathogenicity of pathogenic microorganisms, block impedance to deal with clinically critical disease problems. The application of basic information on QS framework, there may be lacked in the comprehension of the QS structure. Specific QS frameworks have different levels of contrasts in correspondence sections (Morinaga and Wilcox, 2018). Now and again, QS hailing atoms may utilize a microbial language for transmission of various microorganism signals, in which receptors got signals and moved inconceivably. Completely assessment of the QS instrument will indeed make the receptor the essential concern of the examination. All appraisal on the QS structure is determinedly identified with people (Arlotas, 2021). The signal amassing and sign transduction plan of QS receptors in various types of QS frameworks will have more examination in the natural, food and pathogenic microorganisms.

CONCLUSION

Among the microorganism's correspondence through quorum distinguishing is an essential part of microbial life, which engages microorganisms to make an assessment of general microbial population irrespective of types of specie available in the family or non-family and also, as well as, partner or enemy. Greater part distinguishing engages microorganisms to mastermind total practices. In this Review, we have summarized how QS share distinguishing structures work using a parallel game plan of working principles that are fixed in the various physical properties and engineered properties of the AIs, in terms of relating receptors and downstream regulators. Bacterial measures are recognized through QS share frame works and obviously, produced QS modulators share, which further distinguishing overall change bacterial lead on demand. The QS system can handle environmental issues like sewage treatment, characteristic defilement and clearing of harmful and hazardous segments; tackle mechanical issues, for instance, food dealing with and assurance, taking into account the work of QS frame work in the infective microbes, and block impediment for settling the clinically tangled defilement issue. A crucial aspect of bacterial life is QS, which allows bacteria to communicate chemically and count their number as well as identify their neighbours and determine if they are related or unrelated and/or a threat or ally. Using QS, bacteria can create a plan for group actions. This Review summarises the operation of QS systems utilising a comparable set of guiding principles, which are changes in the autoinducers' physical and chemical characteristics, the associated receptors, and their downstream effects. Emulators, since QS is essential for many bacterial functions, it should come as no surprise that efforts to develop synthetic QS modulators are ongoing. It's plausible that the same principles underlying QS networks in bacteria also govern group behaviour in larger creatures. For instance, social insects like honeybees and ants employ QS to choose where to build their nests. Another intriguing example is the fact that animal hair follicles can only regenerate in tandem with neighbouring follicles, and that this group process adheres to a logic resembling QS. The intriguing but now conceivable notion that QS is a general process that operates across the tree of life is raised by this and other recent research. Unmistakable QS systems have varied degrees of contrast in correspondence segments. Here and there, QS hailing iotas could be used as a regular language for signal communication in various microorganisms, yet the path, where all proteins get the signals and turn on downstream sign transduction has changed phenomenally. A through examination of the QS part will without a doubt make the receptor the principal worry of the assessment.

AUTHOR CONTRIBUTIONS

P. Srikanth has performed the some part of writing and preparing the manuscript. D. Sivakumar has done some part of writing, editing and supervision of writing review. J. Nouri is the advisor in writing review article and gave some important intellectual inputs.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percentage
3-OH-MAME	3-hydroxymethyl myristate
3-OH-PAME	3-hydroxy palmitate
AHLs	Acylated homoserine lactones
AI	Autoinducer
AIPs	Autoinducing peptides
ATP	Adenosine triphosphate
DNA	Deoxyribonucleic acid
DPD	4,5-dihydroxy-2,3-pentanedione
DSF	Diffusible signals factor
Epi	Epinephrine
EPS	Extracellular polymeric substance
et al.,	And others
HPLC	High Performance Liquid Chromatography
HSL	Acylated homoserine lactone
IAA	Indole acetic acid
N-AHLs	N-acylated homoserine lactones
NE	Norepinephrine
PGPB bacteria	Plant growth-plant promoting bacteria
PQS	Pharmaceutical quality system
QS	Quorum Sensing
QSIs	Quorum sensing inhibitors
QSIs	QS inhibitors
RNAs	Ribonucleic acids

SAM	S-adenosylmethionine
SRH	S-ribosylhomocysterine
Tdh	Threonine dehydrogenase
TLC	Thin layer Chromatography
TnaA	Tryptophanase

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SPECIAL ISSUE: Eco-friendly sustainable management
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Adaptation variation of easiness on environmental, social, and governance components in the selected sustainability developments

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ABSTRACT

BACKGROUND AND OBJECTIVES: Environmental, Social, and Governance reporting is universally recognized as a pivotal component embraced by the industry to address climate change and serve as a safeguard to the physical and social environments of society. In the absence of global standards, organizations have developed standardized reporting frameworks for companies. This study provides an adaptation easiness measurement and a wide range of environmental, social, and governance disclosure components extracted from several standards. Multiple standards and a broader range of scaling measurements were used in this study to observe the characteristics of each industry where each environmental, social, and governance component is specific. The objective of this study is to investigate how companies in Indonesia comply with various environmental, social, and governance standards, given the importance of identifying variations of easiness on environmental, social, and governance on sustainability reports.
METHODS: Using multi-source analysis, content analysis, and exploratory data analysis, this study identified whether industries in Indonesia adopt selective patterns in the components included in their sustainability reports.
FINDINGS: This study identified 26 environmental, 8 social, and 23 governance popular components, which are components with high environmental, social, and governance report applicability and company adaptability. The environmental components that is easy to adapt primarily center around formal environmental, social, and governance framework data, in social component revolves around customary practices in corporate social responsibility, and in governance component emphasizes corporate reputation. By employing industry-specific environmental, social, and governance components, this study identifies three distinct groups, enabling the formulation of tailored policies to effectively address the unique needs of each group.
CONCLUSION: This study exposes several findings on how companies in Indonesia adopt different components of environmental, social, and governance reports according to their needs, regulations, and analysis complexity. The novelty of this study combined the use of unified comparison components, a wider range of scaling measurements, and specific environmental social, and governance components per-industry type.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
49	8	1

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INTRODUCTION

Sustainability and all its derivatives are the main components of the economic, environmental, and health sectors aimed at addressing the global climate crisis (Adrianto and Sutikno, 2011; Sasongko and Budiarto, 2022; Rodelo-Torrente *et al.,* 2022). Environmental, social, and governance (ESG) reporting is universally recognized as a crucial component embraced by industries to address climate change and act as a guideline for the physical and social environments of society in the long run (Puno *et al.,* 2021; Payus and Sentian, 2022). ESG reporting has significantly improved globally as regulators increasingly emphasize its obligatory implementation and provide financial incentives to companies, while companies are sharing their sustainability responsibilities to increase their accountability (Nicolăescu *et al.,* 2015). In the absence of global standards (Orenstein and Cooke, 2022; Knorringa and Nadvi, 2016), organizations have developed standardized reporting frameworks for companies to use, such as the Global Reporting Initiative (GRI), the Task Force on Climate-related Financial Disclosures (TCFD), and the Sustainability Accounting Standards Board (SASB). Among these frameworks, GRI is the most widely implemented (Ryszawska and Zabawa, 2018), while TCFD focuses more on governance (Cosma *et al*., 2022). Each standard has components that reflect their respective perspectives on sustainability. The number of components that need to be met can pose a challenge for companies. Disparities exist between the global South and the global North in fulfillment ESG reporting. Countries in the global North tend to have better ESG compliance due to the different economic climates, corporate awareness of climate change, and regulations than countries in the global South (Daugaard and Ding, 2022). The development of ESG reporting in the global North is driven by a growing awareness of the need to address the global climate crisis and the increasing importance of sustainability in the corporate world (Drei *et al.,* 2019). This increase is further fueled by increasing demand for sustainability from consumers and investors, as well as by the implementation of more regulations and standards to ensure ESG compliance (Arvidsson and Dumay, 2022; Mavlutova *et al*., 2022). Investments in ESG-focused companies have also increased in the global North, along with the appearance of ESG-based financial products (Hassani and Bahini, 2022). In the global South, the development of ESG reporting is driven by environmental, social, and economic problems, the emergence of new regulatory frameworks, marketing activities, and the development of new technologies (Ng *et al*., 2022; Ubeda *et al*., 2023). ESG reports have become an important tool for meeting the growing demand for accountability from investors, governments, and other stakeholders (Boffo and Patalano, 2020; Signori *et al*., 2021). Companies in the global South face challenges achieving the same quality of ESG reports as companies in the global North due to less advanced technical resources. In Indonesia, various companies have embraced sustainability reporting. The disclosure of ESG reporting in Indonesia is governed by the financial services authority regulation/ *Peraturan Otoritas Jasa Keuangan* (POJK) number 51/POJK.03/2017, which provides guidelines for financial service institutions, issuers, and public companies to implement sustainable finance and deliver sustainability reports. Additional guidelines on sustainability reports in Indonesia are specified in the financial services authority circular letter/ Surat Edaran Otoritas Jasa Keuangan (SEOJK) number 16/SEOJK.04/2021. These two policies are the Indonesian regulations that govern ESG report applications. Companies in Indonesia are obliged to disclose ESG reports annually. The lack of detailed standards within these regulations compels companies in Indonesia to utilize international ESG standards such as GRI and SASB to generate comprehensive and representative reports (Pranesti *et al*., 2022). The publication of the sustainability report is mandatory under the regulations mentioned above, but there are no binding standards that companies in Indonesia must comply with. Non-binding standards provide opportunities for regulatory ambivalence by companies (Ashforth *et al.,* 2014). Recent studies have identified the dynamics of regulatory ambivalence caused by inconsistencies, conflicts, or gaps in regulations or standards governing (Lockie *et al*., 2015), differences in institutional systems and incentives (Agarwal *et al*., 2014), and centrally formulated regulations (Dillon *et al*., 2008). Regulatory ambivalence can lead to several issues, such as regulation conflicts between companies (Gilad, 2014), compliance costs, or non-compliance reputational risk (Whelan *et al*., 2021; Thottoli, 2021), and companies adopting only clear regulations they can understand (Levis, 2006). The lack of regulatory harmonization and standardization in ESG reporting can lead to misleading claims by companies that use different definitions, criteria, methodologies, or benchmarks for sustainability performance. This can undermine the credibility and comparability of ESG reports and make it harder for investors to make informed decisions (Ioannou and Serafeim, 2017). According to the Corporate Knights ranking, Indonesia ranks 36th globally in implementing ESG standards, lagging behind other ASEAN countries such as Thailand (ranked 9th), Malaysia (22nd), and the Philippines (30th) (Scott, 2023). The reason for better ESG implementation in other countries is the comprehensive backing of the regulator, whereby companies that embrace ESG principles receive various incentives, including tax breaks (Zeng and Jiang, 2023). In European Union countries, companies listed on the European Union stock exchange must disclose ESG factors in their annual reports. In Japan, through Japan Stewardship Code, the government requires companies to disclose ESG information through the sustainable finance agency. In China, the government has obliged sustainability reporting requirements for state-owned enterprises and is expected to expand these requirements to other companies, confirming the binding nature of the guidelines. This study builds on the discussions of the interactions between ESG reports and financial performances, ESG rating, and ESG disclosure practices. The connection between ESG reporting and financial gain has recently received increasing interest from scientists. Clark *et al*. (2015) suggest that corporate sustainability standards reduce capital costs. The concept has broadened recently to include financial capabilities, environmental dedication, and community impact (Hastalona and Sadalia, 2021). It has been found that a favorable ESG score positively influences corporate profitability (Kim and Li, 2021). A research series on ESG ratings highlighted the divergence in assessments. Berger *et al*. (2022) found uncertainty regarding the consistent value of ESG indicators across institutions. In China, local ESG ratings are used, aligning with national policies and conditions (Leng *et al*., 2023). Research in the Czech Republic focuses on specific sectors, establishing key ESG performance indicators for investor decision-making and their integration into sustainability reporting (Kocmanová *et al*., 2012). The ESG report and its disclosure practice have been extensively discussed (Laskar and Maji, 2018). Previous studies have investigated various aspects of ESG reporting. For example, Yu and Luu (2021), examined a company's ESG disclosure using the Bloomberg ESG disclosure score, Sharma *et al*. (2020) investigated the relationship between financial performance and the extent of ESG disclosure, and Singhania and Saini (2023) examined the influence of institutional frameworks on ESG disclosure practices. Prior research has examined the impact of the ESG report on financial performance, the quality of the ESG report as assessed by institutional ratings, and the factors influencing ESG report disclosure. This study aims to determine to what extent companies decide to apply specific ESG report components and examines how the gray area influenced by non-binding ESG regulations results in different outputs of ESG reports. In light of these objectives, the study question is: how do ESG reports of companies in Indonesia differ? The study hypothesizes that companies in Indonesia adopt selective patterns in including sustainability components in their ESG reports. This study contributes to the literature by providing adaptation easiness measurement and a wide range of ESG disclosure components extracted from several standards. This study is significant for several reasons. First, this study used multiple standards combined as unified comparison components, filling the gap from the previous research that focused on using a single standard. Second, it utilizes a wider range of scaling measurements to identify the ease of adaptation, which was not previously recognized. Third, the study observes the unique characteristics of each industry, where each ESG component is specific and different from previous research using generalized components to all industries. The objective of this study is to investigate how companies in Indonesia comply with various ESG standards, given the importance of identifying variations in environmental, social, and governance aspects in ESG reports. This study was conducted in Indonesia in 2023.

MATERIALS AND METHODS

This study employed three distinct methodologies: multi-source analysis, content analysis, and exploratory data analysis (EDA). The multi-source analysis involves examining and integrating data from multiple sources, such as various standards and regulations (Levitats and Vigoda-Gadot, 2020). Content analysis is a qualitative research technique used to interpret and draw objective, systematic, and quantifiable inferences by

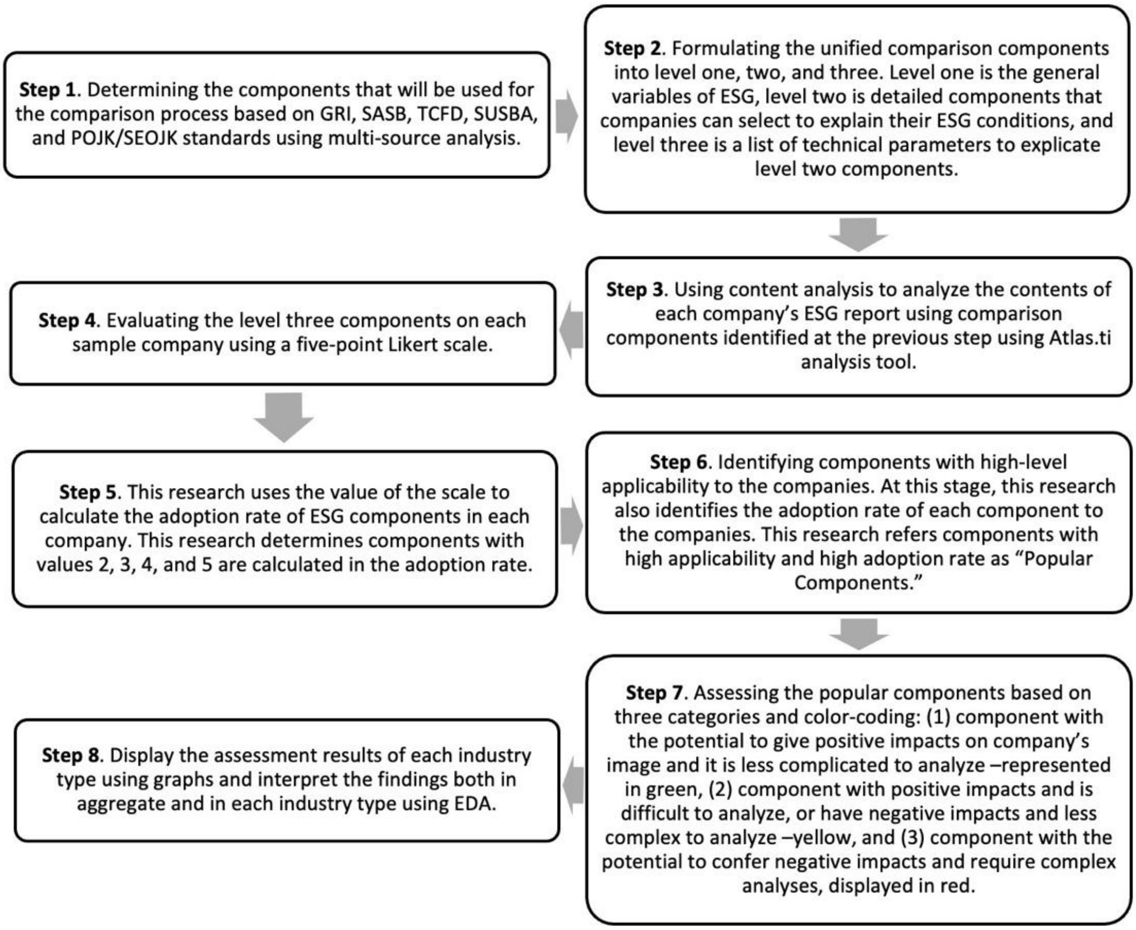

Fig. 1: Study method stages

evaluating textual material, such as reports, against predetermined criteria (Abbot and Monsen, 1979; Daub, 2007; Morhardt *et al*., 2002; Vormedal and Ruud, 2009). EDA is an iterative approach for examining and summarizing data to gain insights and a deeper understanding of its basic characteristics (Arora *et al*., 2021).

There are several analytical steps to identify ESG variations between companies (Fig. 1). First, this study used multi-source analysis (Levitats and Vigoda-Gadot, 2020) to identify unified components derived from international and regional ESG standards. These unified components were then compared with the contents of the ESG reports of each company, necessitating recognition of the general components used in ESG reports. The evaluation of 100 samples of ESG reports was based on the Kompas100 Index, which is a stock index that comprises 100 public companies traded on the Indonesia Stock Exchange. The selected companies exhibit robust liquidity, substantial market capitalization, and commendable fundamentals and performance within the stock market. Out of the 100 sampled companies categorized by stock index classification, 29 distinct industry types were identified, showcasing favorable characteristics within the Indonesian stock market. The international ESG standards utilized in this study are GRI, SASB, and TCFD. GRI is a globally recognized standard for sustainability reporting framework that uses a set of guidelines and indicators. SASB standards identify ESG issues across 77 industries. TCFD standards are organized into 11 recommended disclosures for

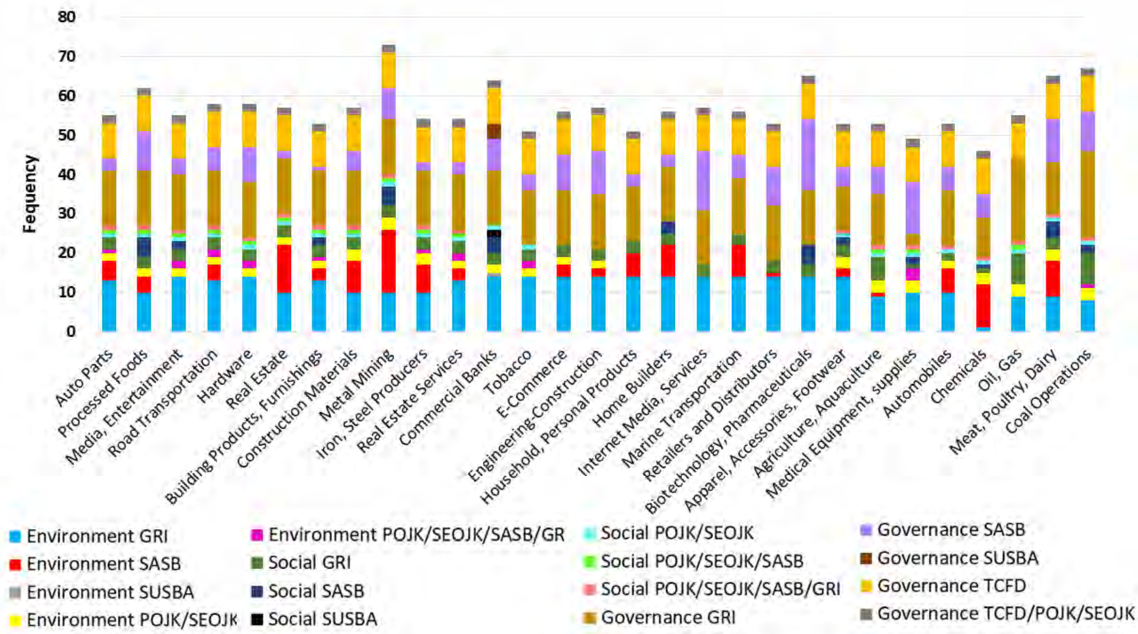

Fig. 2: Distribution of ESG components according to standards

evaluating climate-related risks and opportunities. As for regional ESG standards, this study used POJK and SEOJK, which are Indonesian national guidelines, and Sustainable Banking Assessment (SUSBA), a framework for evaluating environmental and social financial issues in the Asian region. The second step involves formulating the unified comparison components into three levels: level one, two, and three. Each standard has classified its components into environmental, social, and governance categories. Level one component encompasses the general variables identified by each standard, and each general variable consists of multiple detailed components. Level two components are the specific elements that elaborate on the general components. This study identified 109 environmental components, 50 social components, and 212 governance components at level two (Fig. 2). Next, level three components consist a list of technical parameters that must be fulfilled to explicate level two components. There are unified comparison components specific to certain industry types, while several industries can adopt other components. The third step involves content analysis (Morhardt *et al*., 2002), which analyzes each company's ESG report using comparison components from the previous step. The analysis used codes specified for each comparison component with the help of the Atlas. ti analysis tool –assisted qualitative data analysis software. After the coding phase, step four used a five-point Likert scale (Joshi *et al*., 2015) to evaluate the level three ESG components. Scale one suggests that the ESG report does not clarify the comparison components, scale two indicates that the ESG report only partially describes the comparison components, scale three describes the comparison components sufficiently, scale four means the ESG report provides a full description of the comparison components, and scale five indicates a very comprehensive description of the comparison components in the ESG report. The higher the scale value indicates the greater ease of fulfilling the ESG component. This study used the value of this scale to calculate the adoption rate in the next stage. This study determined components with values 2, 3, 4, and 5 calculated in the adoption rate. The fifth step is identifying components with high-level applicability and adoption rates referred to as "Popular Components." Applicability referred to the extent to which a company utilizes a component. For example, an applicability level of 20 percent (%) means that the component can be used by 20% of industry types. The adoption rate referred to the number of companies that include the components in their ESG reports.

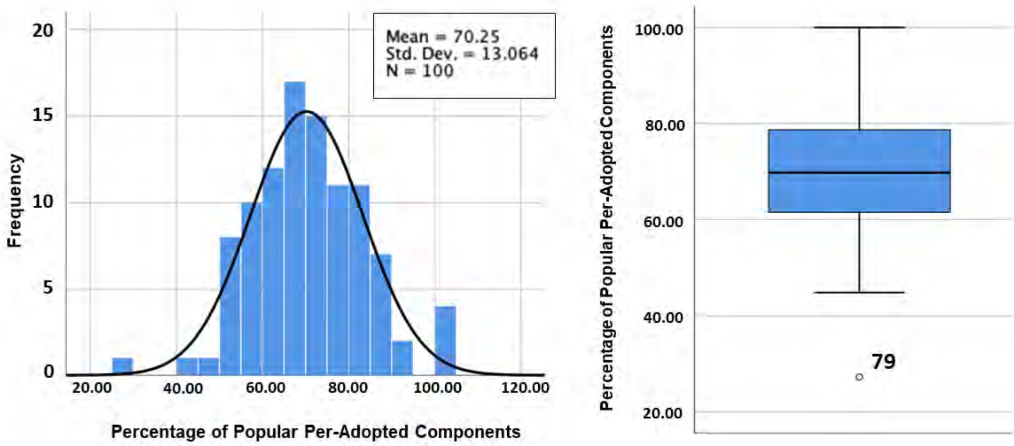

Fig. 3: Distribution of ESG variations

The sixth step is to provide an assessment of popular components based on three categories and color-coded them: 1) has positive impacts on the company's image and less complicated to analyze –represented in green, 2) has positive impacts and difficult to analyze, or has negative impacts and less complex to analyze in yellow, and 3) has the potential to confer negative impacts and require complex analyses, displayed in red. The seventh step is to display the assessment of each industry type using graphs and interpret the findings in EDA (Arora *et al*., 2021).

FINDINGS AND DISCUSSIONS

Indonesia ESG component variations

This study identified ESG components with high adoption rates and classified degree of easiness in data collection and analysis, color-coded as green, yellow, and red (see step 6 in the methods section). Fig. 4, 5, and 6 present ESG components' applicability (Apl) and adoption rate (Adt). The tables also indicate the origin of standards used for each component, including GRI, SASB, TCFD, POJK, and SEOJK.

This study confirmed the validity of the popular components using a normal distribution (D'Agostino, 2017). The popular components were compared to those adopted in the ESG reports to assess the popular components with high coverage percentages. Fig. 3 shows that the lower quartile of the data has a value of 61.54, with an average value of 70.68. These results indicate that the popular components have sufficient coverage to explain the variations in the ESG components of Indonesian companies.

This study identified popular ESG components. Popular environmental and social components tend to analyze data that the company acquires from outside its institution or external parties, while popular governance components analyze the company's management and internal data. In terms of environmental and social components (Figs. 4, 5), companies in Indonesia tend to adopt components that fall into the category of positive impact on a company's image with less complexity in analysis (green colored), as well as components with a positive impact but are complicated to analyze, or vice versa (yellow). Out of the 26 popular environmental components, 42.3% fall into the green category, 46.15% are yellow, and 11.54% are classified as red, indicating potential negative impact and complexity in analysis. In the case of social components, both categories are at an equal value of 50%. For governance components (Fig. 6), this study identified that 26.09% of the components have the potential to confer negative impacts and require complex analyses, indicated by the red color-coding. The governance components categorized have the highest number (43.48%), while the components in the yellow category make up 21.74%. This finding reveals that companies adopt easily adaptable components, supporting previous findings (Pranesti *et al*., 2022) that highlighted companies' application of international ESG standards in generating comprehensive and representative ESG reports. GRI is the most widely adopted standard as a popular component. This finding

GRI **Waste Management** (Waste management for all kinds of non-effluent waste, including hazardous waste) Apl: 20 Adt: 100	GRI **Water and Effluents** (Management of water from consumption to become effluent) Apl: 20 Adt: 100	GRI **GHG Emission** (GHG emissions resulted from industrial activities and their management) Apl: 20 Adt: 95	SASB **Energy Management** (1. Total energy consumed, 2. percentage grid electricity, 3. percentage renewable) Apl: 35 Adt: 88.6
SASB **GHG Emission** (Gross global scope 1 GHG emissions. Regulation, changes from the previous reporting period, calculation methodology, and breakdown of emissions) Apl: 18 Adt: 83.3	GRI **Biodiversity** (List of IUCN red list and its preservation management) Apl: 20 Adt: 80	POJK/SEOJK/GRI **Environmental Performance** (The amount and intensity of energy used, Energy efficiency efforts and achievements) Apl: 23 Adt: 78	GRI **Energy** (Energy consumption within the organization) Apl: 50 Adt: 76
SASB **Water Management** (1. Total water withdrew, 2. Total water consumed, percentage of each in regions with high or extremely high baseline water stress) Apl: 29 Adt: 75.9	SASB **GHG Emission** (Discussion of long-term and short-term strategy to manage scope 1 emissions, emissions reduction targets, and performance analysis on those targets) Apl: 18 Adt: 72.2	POJK/SEOJK/GRI **Environmental Performance** (Amount and intensity of water used, Water efficiency efforts, and achievements made) Apl: 20 Adt: 70	GRI **Energy** (Energy intensity) Apl: 77 Adt: 66
GRI **Water** (Water consumption) Apl: 54 Adt: 64.8	SASB **Water Management** (Description of water management risks and discussion of strategies and practices to mitigate those risks) Apl: 19 Adt: 63.2	GRI **Emissions** (Gross direct scope 1 GHG emissions. Base year, emission factors source, consolidation approach, standards, methodologies) Apl: 57 Adt: 52.6	POJK/SEOJK **Environmental Performance** (Environmental costs) Apl: 85 Adt: 51.7
GRI **Effluents and Waste** (Waste by type and disposal methods) Apl: 73 Adt: 50	GRI **Climate Adaptation, Resilience, and Transition** (Economic performance. Organization's public policy development approach and financial implication related to climate change) Apl: 20 Adt: 50	GRI **Energy** (Reduction of energy consumption) Apl: 77 Adt: 46.8	GRI **Emissions** (Gross location-based energy indirect scope 2 GHG emissions. Base year, emission factors source, consolidation approach, standards, methodologies) Apl: 75 Adt: 44
POJK/SEOJK **Environmental Performance** (Environmentally Friendly Materials) Apl: 85 Adt: 36.5	GRI **Emissions** (Reduction of GHG emissions) Apl: 75 Adt: 36	GRI **Water** (Interaction with water as a shared resource: water management, water-related impacts, goals and targets) Apl: 64 Adt: 35.9	POJK/SEOJK **Environmental Performance** (Complaint aspects related to the environment) Apl: 42 Adt: 35.7
GRI **Effluents and Waste** (Water discharge by quality and destination) Apl: 73 Adt: 35.6	GRI **Environmental Compliance** (Non-compliance with environmental laws and regulations) Apl: 79 Adt: 31.6	Positive impact and less complicated to analyze Positive impact but complicated to analyze/negative impact but less complicated to analyze Negative impact and complicated to analyze Apl Component applicability Adt Adoption rate	

Fig. 4: Popular environmental components

confirms the existence of regulatory ambivalence among companies (Ashforth *et al.*, 2014) due to regulatory gaps (Lockie *et al.*, 2015) in the form of non-binding standards.

In aggregate, companies in Indonesia tend to adopt ESG components that have the potential to have positive impacts on their image and are less complicated to analyze (green color-coded). They also tend to adopt components that have positive impacts but are difficult to analyze, or components that have negative impacts but are less complex to analyze (yellow). Based on the distribution of ESG component variations (Table 1), this study identified that the popular environmental and social components mostly fall into the green and yellow categories (Fig. 7). Although some of the popular governance components are red color-coded, indicating the potential for negative impacts and requiring complex analysis, most of the governance components

GRI **Local Communities** (Local communities engagement, impact management, and development program) Apl: 20 Adt: 95	POJK/SEOJK/ GRI/SASB **Social Performance** (Employment right fulfillment) Apl: 49 Adt: 89.8	POJK/SEOJK **Social Performance** (Commitment of companies to provide equivalent products and/or services to consumers) Apl: 82 Adt: 75.6	GRI **Local Communities** (Activities with local community engagement, impact assessments, and development programs) Apl: 73 Adt: 75.34
POJK/SEOJK **Social Performance** (Corporate social responsibility) Apl: 66 Adt: 69.7	GRI **Rights of Indigenous Peoples** (List of locations and activities where the company engages with indigenous people) Apl: 20 Adt: 45	GRI **Freedom of Association and Collective Bargaining** (Operations and suppliers in which the right to freedom of association and collective bargaining may be at risk) Apl: 78 Adt: 34.6	GRI **Local Communities** (Operations with significant actual and potential negative impacts on local communities) Apl: 73 Adt: 31.5

Positive impact and less complicated to analyze
Positive impact but complicated to analyze/negative impact but less complicated to analyze
Apl Component applicability
Adt Adoption rate

Fig. 5: Popular social components

GRI **Occupational Health and Safety** (Occupational health and safety cases and its management) Apl: 20 Adt: 100	GRI **Forced Labor and Modern Slavery** (Number of forced or compulsory labor) Apl: 20 Adt: 85	GRI **Child Labor** (Number of child labor) Apl: 16 Adt: 81.3	GRI **Occupational Health and Safety** (Occupational health and safety management system standards) Apl: 70 Adt: 77
SASB **Workforce Health & Safety** (1. Total recordable incident rate 2. Fatality rate for (a) direct employees and (b) contract employees) Apl: 17 Adt: 76.5	GRI **Training and Education** (Average hours of training per year per employee) Apl: 76 Adt: 71.0	GRI **Freedom of Association and Collective Bargaining** (Freedom of association and collective bargaining) Apl:20 Adt: 70	GRI **Non-Discrimination and Equal Opportunity** (Non-discriminative action in company operations) Apl: 20 Adt: 70
GRI **Economic Performance** (Direct economic value generated and distributed) Apl: 80 Adt: 68.8	GRI **Employment** (Benefits provided to full-time employees that are not provided to temporary or part-time employees) Apl: 74 Adt: 67.6	GRI **Employment** (New employee hires and employee turnover) Apl: 74 Adt: 66.2	GRI **Anti-Corruption** (Anti-corruption case and management) 20 Adt: 65
GRI **Occupational Health and Safety** (Occupational health services) Apl: 73 Adt: 61.6	GRI **Diversity and Equal Opportunity** (Diversity of governance bodies and employees) Apl: 80 Adt: 60	GRI **Employment Practices** (Employment dynamics and rights fulfillment) Apl: 20 Adt: 60	GRI **Non-Discrimination and Equal Opportunity** (Diversity and equal opportunity) Apl: 20 Adt: 60
GRI **Occupational Health and Safety** (Worker training on occupational health and safety) Apl: 73 Adt: 52	GRI **Occupational Health and Safety** (Hazard identification, risk assessment, and incident investigation) Apl: 73 Adt: 50.7	SASB **Data Security** (Description of approach to identifying and addressing data security risks) Apl: 19 Adt: 47.4	TCFD **Governance** (Describe management's role in assessing and managing climate-related risks and opportunities) Apl: 100 Adt: 47
TCFD **Metrics and Targets** (Disclosure method for scope 1, scope 2, and, if appropriate, scope 3 GHG emissions) Apl: 100 Adt: 46	GRI **Training and Education** (Percentage of employees receiving regular performance and career development reviews) Apl: 76 Adt: 43	SASB **Workforce Health & Safety** (1. Mining safety, 2. Fatality rate, 3. Near miss frequency rate 4. Average hours of health, safety, emergency response training for full-time employees and contract employees) Apl: 19 Adt: 42.1	Positive impact and less complicated to analyze Positive impact but complicated to analyze/negative impact but less complicated to analyze Negative impact and complicated to analyze Apl Component applicability Adt Adoption rate

Fig. 6: Popular governance components

Table 1: ESG Popular Components

E1: Waste management **E2**: Water and effluents **E3**: GHG emissions **E4**: Energy management **E5**: GHG emission-scope 1, regulation and methodology **E6**: Biodiversity **E7**: Environmental performance on energy **E8**: Energy consumption **E9**: Water management-withdraw and consumption in areas with water stress **E10**: GHG emission-scope 1, strategy, target, and performance **E11**: Environmental performance on the water **E12**: Energy intensity **E13**: Water consumption **E14**: Water management risk **E15**: Emissions-GHG scope 1, emissions source, consolidation, and standards **E16**: Environmental cost **E17**: Effluents and waste-by type and disposal **E18**: Climate adaptation, resilience, and transition **E19**: Energy reduction **E20**: Emissions-GHG scope 2, emissions source, consolidation, and standards	**E21**: Environmentally friendly materials **E22**: Emissions reduction **E23**: Interaction with water as a shared resource **E24**: Complaint aspects related to the environment **E25**: Effluents and waste-water discharge by quality and destination **E26**: Environmental compliance **S1**: Local community engagements **S2**: Employment right fulfillment **S3**: Equivalent products and services **S4**: Local community activities **S5**: Corporate social responsibility **S6**: Rights of indigenous peoples **S7**: Freedom of Association and collective bargaining **S8**: Potential negative impacts on local communities **G1**: Occupational health and safety cases and their management **G2**: Forced labor and modern slavery **G3**: Child labor **G4**: Occupational health and safety management system standards	**G5**: Incident and fatality rate **G6**: Hours of training per employee **G7**: Freedom of association **G8**: Non-discrimination actions **G9**: Economic performance **G10**: Benefits for employee **G11**: New employee hires and turnover **G12**: Anti-corruption **G13**: Occupational health services **G14**: Diversity of governance bodies and employees **G15**: Employment practices **G16**: Non-discrimination and diversity **G17**: Worker training on occupational health and safety **G18**: Hazard identification, risk assessment, and incident investigation **G19**: Data security **G20**: Management for climate-related issues **G21**: Metrics and targets **G22**: Percentage of performance development reviews **G23**: Mining incident and fatality rate

still fall into the green and yellow categories. This study identified ESG components with easy adaptation levels by considering the number of companies that scored five on the Likert scales for certain components. The environmental components that companies easily adapt include GHG emissions, environmental performance on energy, environmental cost, environmentally friendly materials, and complaint aspects related to the environment. These four environmental components that are easily adapted by companies are identified from national regulations (POJK and SEOJK). This finding aligns with the results of Singhania and Saini (2023), emphasizing the significance of the ESG framework and highlighting the importance of the ease of the ESG framework as a crucial element in preparing ESG reporting. The social components that companies easily adopt include employment rights fulfillment, activities with local community engagement, corporate social responsibility, and operations with significant actual and potential negative impact on the local community. These easy-adapted social components correlate significantly with the company's practices toward the community, with three out of the four components focusing on social engagement and social impact. The governance components easily adapted by companies include forced labor and modern slavery, child labor, freedom of association, non-discrimination actions, and occupational health services. Four out of the five components pose a risk to the company's reputation. Despite being categorized as risky components, companies perceive them as easily adaptable because the data associated with these components, counterintuitively, contributes to enhancing their reputation. This finding offers a new perspective on reputational risk (Whelan *et al*., 2021; Thottoli, 2021). There are key differences in the ease of adaptation among the ESG components. The environmental component primarily relies on formal ESG framework data, the social component revolves around customary practices in corporate social responsibility, and the governance component emphasizes corporate reputation.

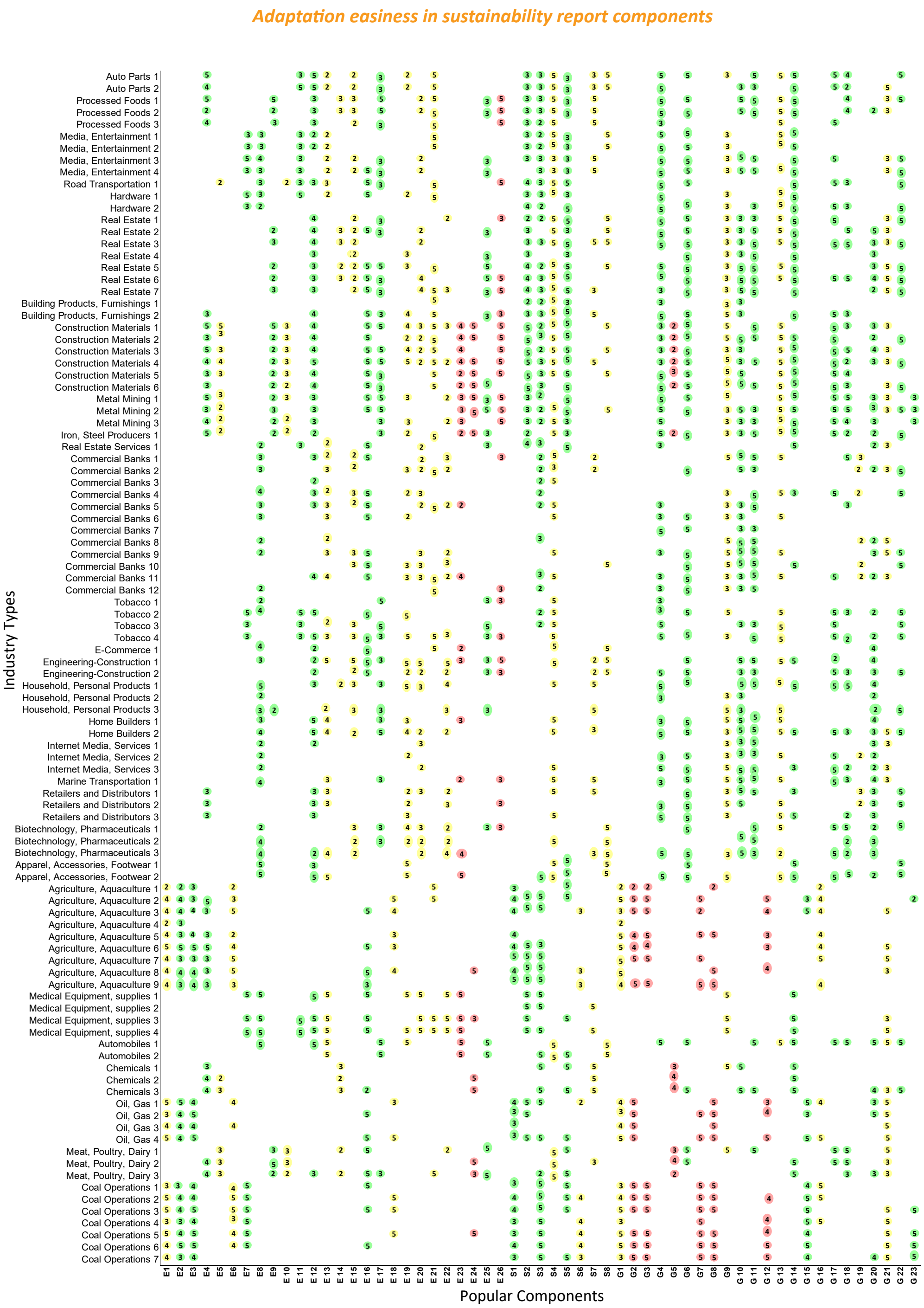

Fig. 7: Distribution of ESG component variations

ESG component variations per-industry

After analyzing 29 types of industries, this study found that each industry type typically prioritizes the use of ESG components that have a positive impact and are less complicated to analyze. Fig. 8 identified three distinct company categories for adopting ESG components.

The first group tends to adopt relatively less

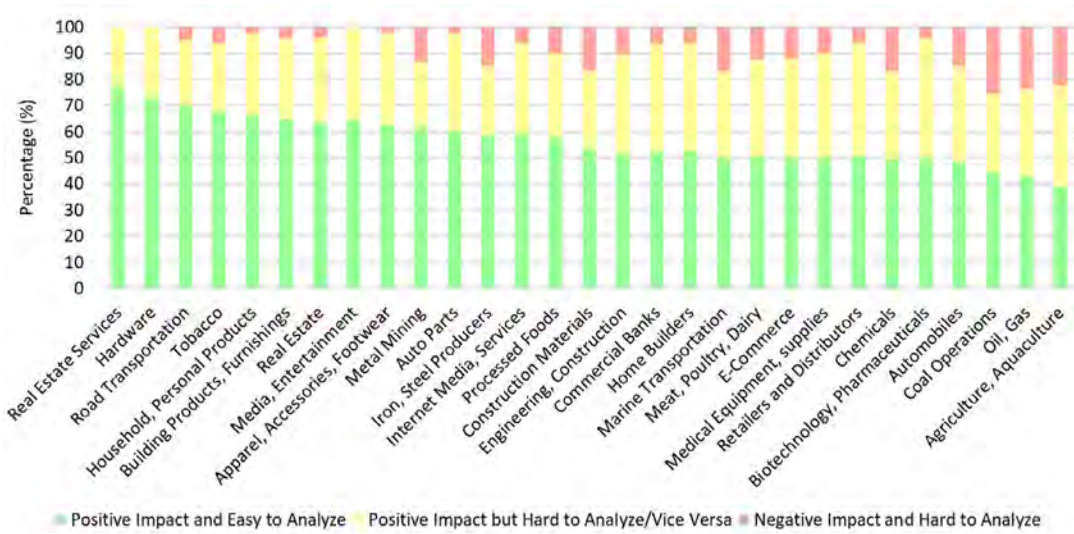

Fig. 8: ESG components between industry types

complicated ESG components, as indicated by the high proportion of green bars. Industries falling into this category include real estate services, hardware, road transportation, tobacco, household and personal products, building products and furnishings, media and entertainment, real estate; apparel, accessories, footwear; metal mining; and auto parts. The second group of industries uses more manageable ESG components. These industries used components with medium (yellow) and high difficulty levels (red) to comply with industry regulations from various sectorial authorities. For example, the chemical industry must adhere to indicators set forth by the American Chemistry Council regarding operational safety, emergency preparedness, and response. Industries in this category include iron and steel producers, internet media services, processed foods, construction materials, engineering and construction, commercial banks, home building, marine transportation, meat, poultry, dairy, e-commerce, medical equipment and supplies, retailers and distributors, chemicals, biotechnology, pharmaceuticals, and automobiles. In the third and final group, industries are mandated by standards to disclose and implement more advanced and comprehensive ESG components. Industries in this category tend to adopt the GRI standard, which includes comprehensive assessment components. Industries operating within coal operations, oil and gas, and agriculture and aquaculture fall into this category. The findings confirm that by utilizing industry-specific ESG components, it is possible to identify distinct groups of industries in Indonesia. These distinct groups can serve as the basis for formulating tailored policies to address the unique needs of each group.

CONCLUSIONS

This study confirms that companies in Indonesia selectively adopt sustainability components in their ESG reports, primarily focusing on easily disclosed ESG components. The study contributes to the literature by providing a measurement of adaptation and a wide range of ESG disclosure components extracted from various standards. Multiple standards were combined as unified comparison components, and scaling measurements were used to identify the ease of adaptation, applying specific ESG components for each industry characteristic. Unified components were derived from international and regional ESG standards and were used to analyze companies' ESG reports. The study identified 109 environmental components, 50 social components, and 212 governance unified components. Through EDA on the unified components, the study identified 26 environmental, 8 social, and 23 governance popular ESG components based on their high applicability and adoption rates. These popular components were categorized into three distinct categories, differentiating them according to their impacts on image and analysis difficulty. Indonesian companies prioritize ESG components with a positive impact that are less complex to analyze. Using the Likert scale in content analysis, this study identified ESG components with an easy adaptation level. The study confirms that the characteristics of easily adaptable components underscore the significance of the ESG framework for environmental components, establish a strong correlation between adaptability and company practices toward the community for social components, and emphasize governance components that contribute to enhancing company reputation. The findings confirms that utilizing industry-specific ESG components enables the identification of distinct groups of industries in Indonesia, which can serve as the basis for formulating tailored policies to address the unique needs of each group. The popular components identified in this study can serve as a foundation for ESG report regulations in Indonesia.

AUTHOR CONTRIBUTIONS

F.R. Sutikno performed the eight steps of analysis and oversaw the whole process. N.A. Sasangko executed data preparation and the scoring process. I.N. Djarot carried out the preparation of graphs and drawings. H.S. Dillon conducted the exploratory data analysis (EDA) interpretation.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
Adt	Adoption rate
Apl	Component applicability
ASEAN	Association of southeast asian nations
EDA	Exploratory data analysis
ESG	Environment, social, governance
GHG	Greenhouse gas
GRI	Global reporting initiative
IUCN	International union for conservation of nature
NMFR	Near miss frequency rate
N	Number of data
OJK	Otoritas jasa keuangan/financial services authority
POJK	Peraturan otoritas jasa keuangan/ financial services authority regulation
SASB	Sustainability accounting standards board
SEOJK	Surat edaran otoritas jasa keuangan/ financial services authority circular letter
Std. Dev.	Standard deviation
SUSBA	Sustainable banking assessment
TCFD	Task force on climate-related financial disclosures

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Podcasts

SPECIAL ISSUE: Eco-friendly sustainable management
CASE STUDY

Effects of effluent recirculation on two-stage anaerobic digestion in treatment of biodegradable municipal solid waste

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ABSTRACT

BACKGROUND AND OBJECTIVES: Advantages such as high stability and high biogas production when recirculating the effluent stream in two-stage anaerobic digestion systems have been demonstrated on a variety of substrates, but there is limited information regarding the use of this practice on organic municipal waste. Therefore, this study aimed to investigate how effluent recirculation affects the two-stage anaerobic digestion of biodegradable municipal solid waste.

METHODS: Firstly, biodegradable municipal solid waste substrate was fermented under conditions of 12 percent initial total solids and a temperature of 36 degrees Celsius for 5 days. After that, the substrate continued to be diluted using tap water or the effluent stream with a rate of 2:1. In the case of using the effluent stream, the experiment was further performed with dilution rates of 3:1, 1:1, and 1:2. Then, the liquid part was collected and pumped into the methane reactor at an organic loading rate of 7.64 grams of total solids per liter per day at 36 degrees Celsius. The methane reactor was an up-flow reactor that contained both granular sludge and suspended sludge. The effectiveness of the experimental stages was evaluated through biogas production and chemical oxygen demand removal.

FINDINGS: In the fermentative reactor, using the effluent stream to dilute solid-state feedstock helped keep the reactor stable at pH 5.5 without alkali addition. In the case of using tap water for dilution, it required a dose of 115.8 grams and 75.3 grams of sodium hydroxide per kilogram of volatile solids to attain pH conditions at 6.5 and 5.5, respectively. Maintaining the reactor at pH 6.5 increased the concentration of fermentation products compared to pH 5.5, including 5.9 percent total chemical oxygen demand, 5.5 percent soluble chemical oxygen demand, and 10.6 percent total volatile fatty acids. In the case of recirculating the effluent stream in the methane reactor, increasing the dilution rate from 0.5 to 3.0 resulted in a methane yield of 227.5-278.9 milliliter per gram of volatile solids and 85-93 percent chemical oxygen demand removal. The methane reactor's best digestion performance was attained at recirculation rate 2. Methane formation mainly occurred in granular sludge via the hydrogenotrophic pathway. Methane formation in suspended sludge occurred in a secondary manner, mainly via both the hydrogenotrophic and acetotrophic pathways. Among methanogen families, Methanobacteriaceae was found to have the highest relative abundance (7.5 percent in granular sludge and 0.8 percent in suspended sludge).

CONCLUSION: Recirculating the effluent provided significant benefits, including the ability to stabilize the hydrolysis process and increase the methane yield. A recirculation rate of 2 to obtain a total chemical oxygen demand of 35.2 grams per liter was the best condition for methanogenesis. Acetotrophic methanogens were better adapted to difficult conditions than hydrogenotrophic methanogens. The formation of methane mainly occurred in granular sludge via a dominant hydrogenotrophic pathway. Methane formation in suspended sludge occurred in a secondary manner, mainly via both the hydrogenotrophic and acetotrophic pathways. Among methanogen families, Methanobacteriaceae was found to have the highest relative abundance.

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INTRODUCTION

Two-stage anaerobic digestion (TAD) is attracting the attention of researchers due to its stability, flexibility, and capacity to function effectively despite fluctuations in the waste stream (Dinh *et al*., 2020). In the TAD process, the substrate is hydrolyzed in a fermentative reactor (FR), then the substrate stream is converted to methane (CH_4) in a methanogenic reactor (MR) (Dinh *et al*., 2020; Srisowmeya *et al*., 2020). In this way, the TAD system allows different groups of microorganisms to grow under their own optimal conditions (Dhayalan and Karuppasamy, 2021; Manjarrez Paba *et al*., 2021; Samimi and Shahriari Moghadam, 2020; Nuryadin and Imai, 2021). This is the basis for a robust system that is able to resist fluctuations in characteristics such as potential hydrogen (pH), organic concentration, and organic loading rate (OLR) (Dinh *et al*., 2020). In the FR, hydrolysis/acidogenesis converts the carbon of high-molecular-weight compounds into volatile fatty acids (VFAs). Although the microorganisms in charge of these processes could work well under acidic conditions, they require a longer retention time than usual to ferment substrates (Dinh *et al*., 2020; Nabaterega *et al*., 2021). In the MR, methane formation occurs due to the activities of strict anaerobes. They are extremely sensitive to pH conditions, being unable to operate at pH < 6.2 and potentially collapsing at pH <5.5 (Gerardi, 2003; Nabaterega *et al*., 2021). Therefore, using alkali addition for pH control is necessary for anaerobic digestion (AD) systems. This effort would increase operational costs in full-scale plants (Notodarmojo *et al*., 2022). To prevent the need for alkali addition in TAD, Romli *et al*. (1994) introduced the effluent from the MR to the FR in a wastewater treatment system. They reported that the use of the recirculation stream removed dissolved carbon dioxide (CO_2), (weak acids) from the gas phase, causing a decrease in caustic consumption. The effects of effluent recirculation on TAD systems have also been investigated for some organic wastes such as cattle feed (Kovalev *et al*., 2021), starch and cotton (Aslanzadeh *et al*., 2013), swine manure (Chen *et al*., 2021), leafy waste materials (Zuo *et al*., 2015), citrus waste (Wikandari *et al*., 2018), food waste (Ding *et al*., 2021), and vegetable waste (Zuo *et al*., 2013). For starch and cotton, Aslanzadeh *et al*. (2013) demonstrated that using effluent recirculation provided considerable benefits in terms of improved CH_4 yield and process stability. For vegetable waste, Zuo *et al*. (2013) proved that effluent recirculation reduced volatile fatty acid (VFA) inhibition and increased biogas generation at a high organic loading rate (OLR) due to the effects of dilution and pH correction. For citrus waste, Wikandari *et al*. (2018) reported that the system using effluent recirculation produced a higher CH_4 yield compared to that without recirculation. For food waste, Ding *et al*. (2021) showed that the liquid effluent of the MR supplied base buffering and acid washing to the FR. Similar research on biodegradable municipal solid waste (BMSW) is still limited in the literature. The majority of the interest in TAD has been focused on MRs because methanogens have a much slower growth rate and are much more sensitive than other microbial groups. Many studies have shown that using granular sludge (GS) can help overcome those weaknesses due to advantages such as high microbial concentration, superior settling property, and high resistance to toxic compounds (Azizan *et al*., 2022; Cruz-Salomón *et al*., 2019). These dense particles consist of an intertwined mixture of symbiotic anaerobic microorganisms that work together. These microbial groups arrange themselves in an orderly fashion, forming a multilayered structure (McHugh *et al*., 2003). The outside layer consists of an acidogenic bacterial group that acidifies complex organic matter into short-chain VFAs as food for the inner microbial layers. Moreover, the fact that free hydrogen-consuming microorganisms are found in the exterior layer helps to avoid hydrogen diffusion into the second layer (Pol *et al*., 2004). Therefore, granular sludge might reduce the impacts of substrate fluctuations such as pH, organic concentration, and organic loading rate (Piri and Sepehr, 2022). The second layer contains acetogens and hydrogenotrophic methanogens. This layer surrounds the central core which contains acetotrophic methanogens. Therefore, sludge granules can be regarded as well-balanced microecosystems (McHugh *et al*., 2003). However, studies of the application of anaerobic granular sludge to deal with BMSW are still limited in the literature. The objective of this study is to investigate the effects of effluent recirculation on the TAD of BMSW in an MR in the presence of GS. The assessment is based on the results of biogas quality, biogas quantity, and chemical oxygen demand (COD) removal. The experiment was conducted in Japan in 2019-2020 and data analysis was carried out in Vietnam in 2021-2022.

MATERIALS AND METHODS

Substrate, anaerobic microorganisms, and an anaerobic reactor are required to conduct any anaerobic digestion assay. In this study, the substrate was collected from BMSW sources. The microorganisms and the anaerobic reactor were in good working condition. The reactor was operated at different stages to suit the intended purpose. The evaluation results were based on the physicochemical analysis of the material flow.

Substrate

The substrate contained 90 percent (%) BMSW and 10% inoculum on a wet basis. It was sliced into small-sized particles and ground, then stored at 0-4 degrees Celsius (°C) until used. Characteristics of BMSW, inoculum, and feedstock are shown in Table 1.

Experimental setup

The experimental model simulating the TAD system is shown in Fig. 1. The system was operated at 37°C and consisted of one FR, one MR, and one buffer tank between these two reactors. Firstly, the feedstock was fermented in FR with a retention time (RT) of 5 days (d). According to the reviews of TAD systems by Dinh *et al*. (2020), the acidogenesis of BMSW in a mesophilic environment proved successful with RT ranging from 2 to 5 days. The acidogenesis in this study was conducted with a five-day RT for safety reasons. The hydrolysate was then diluted to lower the concentration before being filtered (1mm) to remove particles (nonhydrolyzed materials). Finally, the hydrolysate liquid was injected into MR at an organic loading rate (OLR) of 7.64 grams of volatile solids per liter per day (g-TS/(L.d)). The MR was an up-flow reactor that contained both GS and suspended sludge (SS). There were two effluent recirculation circles including R1 (dilution in FR) and R2 (dilution in MR), as shown in Fig. 1. While recirculation in FR (R1) was to adjust TSs of the fresh feedstock at a concentration of 120 grams per liter (g/L), recirculation in MR (R2) was to reduce the hydrolysate concentration. The recirculation rate (n) of R2 was set to 3:1 for stage EX3, then to 2:1, 1:1, and 0.5:1 for stages EX4, EX5, and EX6, respectively.

Nonrecirculation trials (EX1 and EX2) were carried out with tap water for dilution instead of using the effluent stream. During fermentation, the pH of trials EX1 and EX2 was adjusted to 6.5 and 5.5, respectively,

Table 1. Physicochemical properties of the materials

Characteristics	BMSW	Inoculum	Feedstock
Total solid - TS (%)	26.88	20.01	26.19
Volatile solid - VS (%TS)	66.24	76.82	67.05
Carbon - C (%TS)	44.81	45.22	44.84
Nitrogen - N (%TS)	2.54	1.24	2.44
Carbon to nitrogen (C/N)	17.64	36.37	18.37

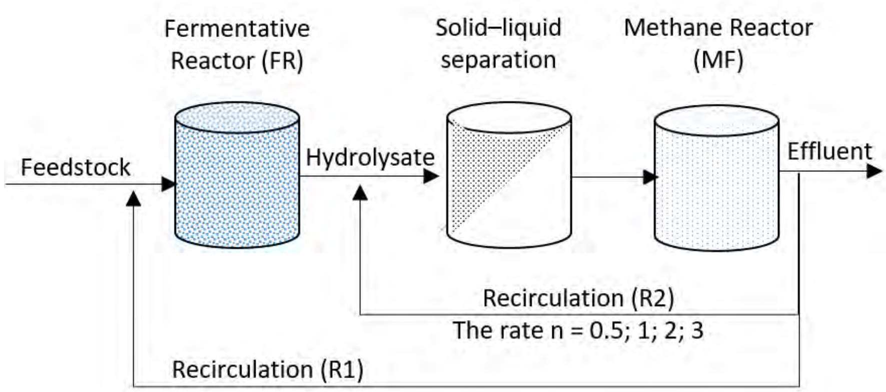

Fig. 1: Experimental model

using a 10 mol (M) solution of sodium hydroxide (NaOH).

Physicochemical analysis

For solid samples, the carbon, nitrogen, TS, and VS composition of the substrate were analyzed following standard methods, with the details presented by Dinh *et al*. (2018). For aqueous samples, pH was determined using a pH meter (Total Meter—Taiwan). Total COD (TCOD) and soluble COD (SCOD) were analyzed using a spectrophotometer (MD600, Lovibond, UK). VFA composition of the liquid hydrolysate was determined using a GC-14A gas chromatograph (Shimadzu, Japan). Biogas components were analyzed using a GC-2014 gas chromatograph (Shimadzu, Japan) equipped with a packed column and conductivity detector.

Microbiological analysis

Microbiological analysis was performed for both GS and SS. The details of deoxyribonucleic acid (DNA) extraction procedures are described in the literature. Cell lysis of 0.2 g wet-weight samples was achieved by beating them with sterile zirconium beads in the presence of sodium dodecyl sulfate (4% weight per volume), 0.5 mol sodium chloride, and 0.05 M ethylenediaminetetraacetic acid. Most of the impurities and the sodium dodecyl sulfate were then removed by precipitation with 10 M ammonium acetate. The nucleic acids were recovered by precipitation with isopropanol. After that, the isolation of genomic DNA was purified via sequential digestions with RNase and proteinase K, before using the QIAamp DNA Stool Mini Kit columns. The DNA amplification was performed following the method described by Nguyen *et al*. (2020). The method used a quantitative real-time polymerase chain reaction (PCR) targeting the V4 region of the 16S rRNA gene (forward: 5'-ACACTC TTTCCCTACACGACGCTCTTCCGATCTGTGCCAGCMGCCGCGGTAA-3'; reverse: 5'-TGACTGGAGTTCAGACGTGTGCTCTTCCGATCTGGACTACHVGGGTWTCTAAT-3'). Details of the protocol are attached in the report by Nguyen *et al*. (2020). The raw sequences from the archive were analyzed using the quantitative insights into microbial ecology (QIIME, version 1.9.1) program (Pagliano *et al*., 2019). JMP software (version 11; SAS Institute) was used to perform statistical analysis on all data. A nonparametric Wilcoxon test was used to examine the statistical significance of the discrepancies.

RESULTS AND DISCUSSION

Due to its important role in defining the success and performance of methanogenesis, the microbial structure in the reactor is presented before the results are discussed according to the study objectives.

The microbial community in the methane reactor at the family level

The structure of the microbial community at the family level in GS and SS is presented in Fig. 2. The relative abundance (RA) of methanogens in GS accounted for 11.8% of the total microbial organisms, including *Methanobacteriaceae* (7.5%), *Methanosaetaceae* (2.9%), and *Methanomassiliicoccaceae* (1.4%). The RA of the methanogens in SS accounted for only 2.5%. The RA of methanogens in GS in this study was also significantly higher than that reported in the literature, for example, Guo *et al*. (2015) (5.6%), Qin *et al*. (2018) (3.18%), and Shin *et al*. (2019) (>1%). This suggests that GS favors the growth of methanogens due to its multilayer structure and symbiotic interaction mode. Within methanogens, *Methanobacteriaceae* is known as a hydrogenotrophic family, *Methanosaetaceae* is considered an acetotrophic one, and *Methanomassiliicoccaceae* represents a methylotrophic one (Söllinger and Urich, 2019; Ziganshin *et al*., 2016). This was reflected in the fact that CH_4 formation mainly occurred in GS via a dominant hydrogenotrophic pathway using CO_2 and hydrogen (H_2) as substrates. Methane formation in suspended sludge occurred in a secondary manner, mainly via both the hydrogenotrophic and acetotrophic pathways. Methane synthesis by the methyl group in the reactor was not significant.

Excluding methanogens, the most abundant bacterial families found in GS in descending order were *Syntrophomonadaceae* (11.8%), *Porphyromonadaceae* (8.2%), *Ruminococcaceae* (6.5%), *Syntrophaceae* (5.8%), and *Anaerolineaceae* (4.9%). The family *Syntrophomonadaceae* plays the role of oxidizing fatty acids with 4-18 carbons into acetate and short-chain fatty acids (Schink and Muñoz, 2014). Members of this family are predominantly found in syntrophic associations with methanogens (Hashemi *et al*., 2021; Schink and Muñoz, 2014). *Porphyromonadaceae* is known to be a family of acid-forming obligate anaerobic bacteria and has been previously identified in digesters dealing with municipal solid waste and animal waste (Chen *et*

Table 2: Operation of the TAD system

Test	Fermentation			Methanogenesis		
	TS	RT	pH	Dilution rate/ recirculation rate (n)	RT (days)	Total COD/soluble COD (g/L/g/L)
EX1	12 % (using tap water for dilution)	5 days	5.5	2.0	3.51	31.7/19.8
EX2			6.5	2.0	3.51	33.5/21.0
EX3	12 % (using effluent stream for dilution)	5 days	Uncontrolled	3.0	2.63	26.7/16.7
EX4				2.0	3.51	35.2/21.8
EX5				1.0	5.26	52.6/32.4
EX6				0.5	7.02	71.8/44.1

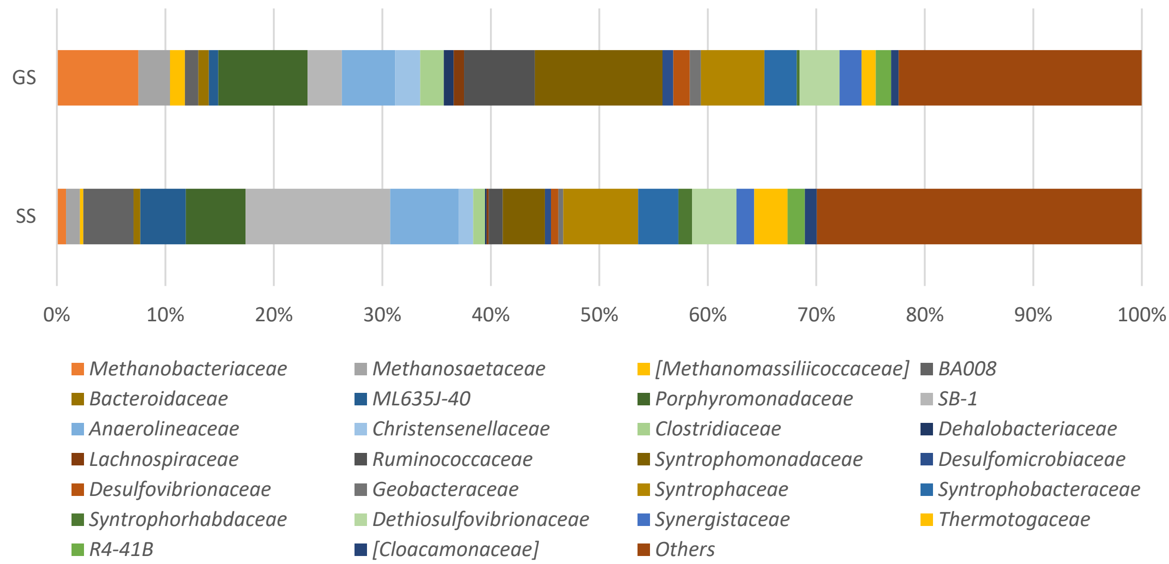

Fig. 2: Relative abundance of microorganisms in methane reactor at the family level

al., 2016). The family *Ruminococcaceae* has often been determined in the feces of animals (Pampillón-González *et al.*, 2017). They can hydrolyze a wide range of polysaccharides via several processes, including the production of cellulolytic enzymes (Morrison and Miron, 2000). They are also known to create VFAs and can ferment both hexoses and pentoses (Scott *et al.*, 2014). Blasco *et al.* (2020) found a positive significant relationship between VFA production and the RA of the microbial order *Clostridiales* containing the family *Ruminococcaceae*. They are also known to live in symbiosis with methanogens. The family *Syntrophaceae* contains four genera: *Syntrophus*, *Smithella*, *Desulfobacca,* and *Desulfomonile* (Kuever, 2014). *Syntrophus* and *Smithella* members are *chemoorganoheterotrophs* that may oxidize organic substrates partially to acetate or fully to CO_2. Members of the *Desulfobacca* and *Desulfomonile* genera are described as autotrophs that thrive on H_2 and CO_2 and can utilize sulfate, sulfite, and thiosulfate as electron acceptors that are reduced to sulfide. All members are mesophilic anaerobes and require anoxic media for growth (Nakasaki *et al.*, 2020). *Syntrophaceae* grows well in a long-chain fatty-acid-rich environment. The cultured *Anaerolineaceae* members ferment carbohydrates and/or peptides (Zhu *et al.*, 2017). Because they have a multicellular filamentous shape, *Anaerolineaceae* are significant bacteria for sludge granulation and granular structure maintenance. As a result, they have been discovered in both the outer layer and interior of sludge particles (Yamada and Sekiguchi, 2009). It has been

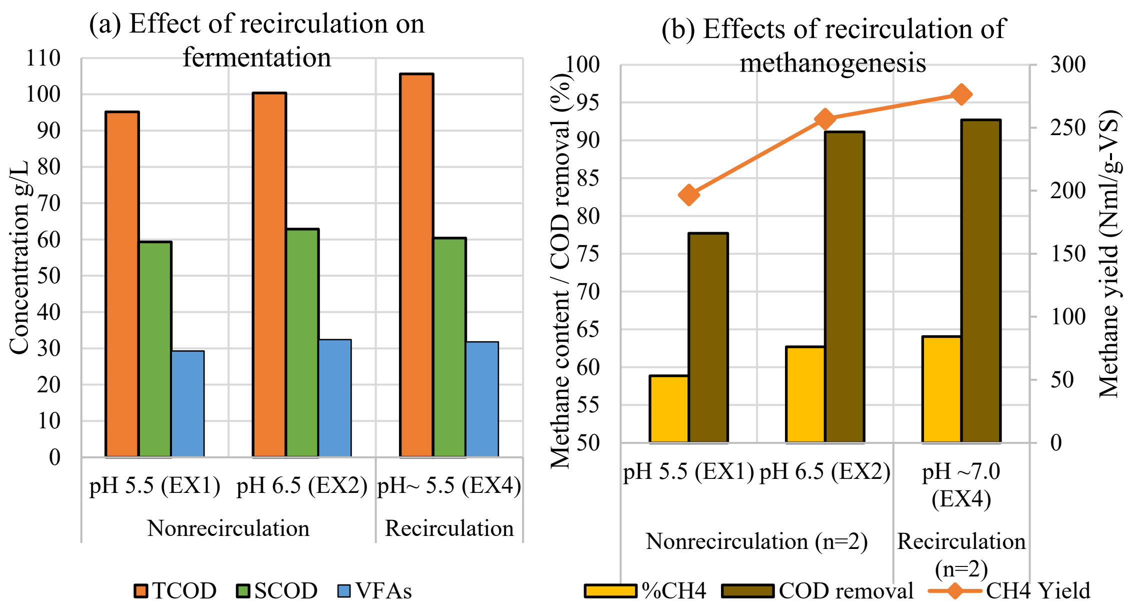

Fig. 3: Results at experimental stages

suggested that *Anaerolineaceae* has a symbiosis with *Methanosaeta* because *Methanosaeta* uses acetate produced by *Anaerolineaceae* (Owusu-Agyeman *et al*., 2019). The total RA of these acidogens/acetogens in SS (25%) was much lower than that obtained for those in GS (37%), reflecting that most VFAs were converted by microorganisms in GS.

Recirculation versus nonrecirculation

In the current study, maintaining the pH at 5.5 (EX1) required 74.4 grams of sodium hydroxide per kilogram of volatile solids (g/kg-VS). The alkali consumption increased to 114.4 g/kg.VS to attain a pH of 6.5 (EX2). For kitchen waste, Zhang *et al*. (2005) added a dosage of 272.1 mg-NaOH/g-TS to attain fermentation at pH 5. In another study, Sambusiti *et al*. (2013) reported that a dosage of 10 mg-NaOH/g-TS helped to maintain fermentation at pH 6.7 for wheat straw and at pH 6.3 for ensiled sorghum forage, respectively. Therefore, alkali consumption during fermentation depends not only on the pH level but also on the type of raw materials used. In experiment EX3, returning the effluent to the FR helped maintain a pH level comparable to that in EX1 without the need for alkali addition. This result can be explained by the following points. High-protein-content BMSW is converted into amino acids in the FR (Campuzano and González, 2016; Gerardi, 2003). In the MR, amino acids are further degraded to give ammonia (NH_3), which is a weak-base buffer (Chen *et al*., 2015; Gerardi, 2003). Furthermore, the majority of the VFAs fed into the MR are transformed into biogas. As a result of these factors, the effluent from the methane reactor has a high alkalinity. Thus, mixing the feedstock with the effluent stream can help to maintain a stable pH in the FR. Fig. 3(a) depicts the characteristics of the fermentative products from various experimental stages. The results from EX1 and EX4 did not significantly differ from one another. This reflects that the use of the effluent stream not only does not have any adverse effects on hydrolysis/acidogenesis but can also maintain pH conditions at a relevant level for fermentation. The influence of pH on fermentation was shown in the results between EX1 and EX2, whereby maintaining the reactor at pH 6.5 increased the fermentation products by 5.9% for TCOD, 5.5% for SCOD, and 10.6% for total VFAs when compared to the reactor maintained at pH 5.5. A similar trend was also reported by Veeken *et al*. (2000), who found that increasing the pH

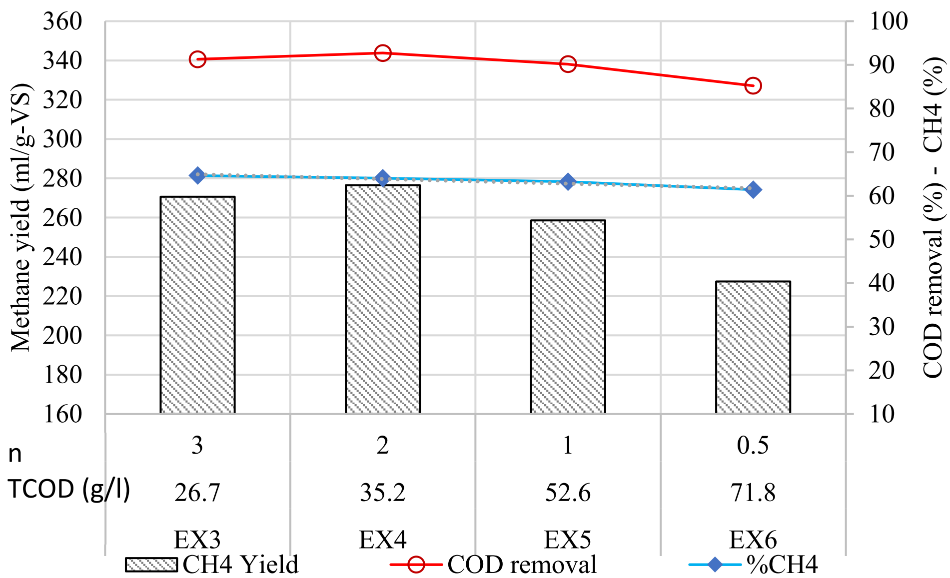

Fig. 4: Effects of different recirculation rates (n) on methanogenesis

from 5.0 to 7.0 greatly boosted the hydrolysis rate. These findings can be explained by the considerable positive association between enzymatic activity and pH in the range of 5.0-6.5 (Sanders, 2001). Following fermentation, the hydrolysate was diluted at a rate of n=2 before being introduced into the MR. While the pH in the nonrecirculation tests (EX1 and EX2) did not vary significantly, the pH condition in the recirculation examination (EX4) rose to 7.0. The various characteristics of the fermentation products produced differences in CH_4 yield, CH_4 concentration, and COD removal, as shown in Fig. 3(b). In general, the current investigation was consistent with the findings of Aslanzadeh *et al*. (2013) and Zuo *et al*. (2014), who found that recirculation helped obtain better performance than nonrecirculation.

The influent with a neutral pH (7.0) provided the best conditions in the MR with a CH_4 yield of 276.3 milliliters per gram of volatile solids (mL/g.VS). The influent with a slightly acidic pH (6.5) resulted in a 2% decrease in CH_4 concentration and a 7% decrease in CH_4 production. The influent with an acidic pH level (5.5) (EX1) exhibited a 28.8% and 8% reduction in CH_4 yield and CH_4 concentration, respectively. These findings indicate that methanogens thrive in pH-neutral environments. According to the literature, there are two main different reactions that produce CH_4: (1) acetotrophic methanogens digest acetic acid to produce CH_4 and CO_2, and (2) hydrogenotrophic methanogens create CH_4 from CO_2 (Dinh *et al*., 2020; Gerardi, 2003). These two microbial groups respond differently to environmental changes. The CH_4 composition of biogas changes as a result of the ratio of reaction (1) to reaction (2) altering. From the link between pH levels and CH_4%, it was observed that acetotrophic methanogens were better adapted to acidic circumstances than hydrogenotrophic methanogens.

Effects of different recirculation rates

Increasing the recirculation rate (n) from 0.5 to 3 led to changes in CH_4 yield (227.5-278.9 mL/g-VS) and COD removal (85.2-92.7%). Fig. 4 provides specific information regarding the impact of various recirculation rates on the performance of the MR.

The MR's best methanogenic performance was attained when the recirculation rate was n = 2 and the TCOD of the influent was 35.2 mg/L. Recirculation rate n = 3 offered benefits such as quicker substrate diffusion and interaction with lower substrate concentrations (TCOD = 26.7 g/L). However, operation at rate n=3 had a significantly lower retention time (RT) than operation at rate n=2. RT should be long enough for anaerobes to make contact with and break down substrates (Dinh *et al*., 2020; Mshandete *et al*., 2004). In this study, it was observed that operation at rate n=3 was slightly less effective than operation at n=2, probably due to the shorter contact period between the anaerobes and the substrate. Zuo *et al*. (2014) corroborated the same trend and observed that decreasing the recirculation rate to dilute the COD concentration from 21 grams of oxygen per liter (g-O_2/L) to 6.8 g-O_2/L resulted in a 6% drop in CH_4 yield and an 8% reduction in COD removal. Even during the highest recirculation rate, they discovered biomass washout. In a different study, Yu *et al*. (2000) confirmed that high n values would cause an excessive rise in the effective loading rate in the methanogenic reactor, which would then cause a gradual increase in the concentration of organic output and a reduction in efficiency. Dilution of the influent stream influences substrate diffusion or transmission and may result in a slower reaction rate, which lowers process efficiency. According to Mshandete *et al*. (2004), long retention times for anaerobic up-flow reactors produced a laminar flow that enhanced methanogenesis. However, a higher influent concentration is established at lower recirculation rates. Because of this, utilizing recirculation rates of n=1 and 0.5 resulted in a worse methanogenic performance than using n=2. At recirculation rate n=1, the influent with a TCOD of 52.6 g-O_2/L resulted in a 6.5% and 2.7% reduction in biogas yield and COD removal, respectively. At n=0.5, the TCOD concentration of the effluent was 71.8 g-O_2/L, leading to an 8.1% and 17.7% reduction

Table 3: The effects of effluent recirculation on TAD systems with different types of biodegradable wastes

Feedstock	TAD systems	Findings	Sources
Cattle feed	$CSTR^{1st}$ – $CSTR^{2nd}$ $Thermophilic^{1st}$ – $Thermophilic^{2nd}$	A low recirculation rate can improve the performance of the TAD process. The best recirculation rate was 0.11 bringing a net energy of 7.7 kJ/g-VS.	Kovalev *et al*., 2021
Starch and cotton	$CSTR^{1st}$ – $UASB^{2nd}$ Thermophilic – $Mesophilic^{2nd}$ OLR 4.0-10 g-VS/(L.d)	The use of effluent recirculation improved the overall performance and stability of the process.	Aslanzadeh *et al*., 2013
Swine manure	$CSTR^{1st}$ – $CSTR^{2nd}$ $Thermophilic^{1st}$ – $Mesophilic^{2nd}$ OLR 1.76 g-VS/(L.d)	Using the digestate recirculation increased CH_4, VS removal, and reaction rate by 9.92 ± 5.08, 5.22 ± 1.94, and 9.73 ± 12.60%, respectively.	Chen *et al*., 2021
Leafy waste materials	$CSTR^{1st}$ – $CSTR^{2nd}$ $Mesophilic^{1st}$ – $Mesophilic^{2nd}$ OLR 2.6 – 3.0 g-VS/(L.d)	The system without recirculation was susceptible to overloading and volatile fatty acid (VFA) utilization was inhibited in the methanogenic reactor.	Zuo *et al*., 2015
Citrus waste	$CSTR^{1st}$ – $UASB^{2nd}$ $Mesophilic^{1st}$ – $Mesophilic^{2nd}$ OLR 5.0 g-VS/(L.d)	The system using effluent recirculation produced a higher CH_4 yield and was more stable compared to that without recirculation.	Wikandari *et al*., 2018
Food waste	$CSTR^{1st}$ – $CSTR^{2nd}$ $Mesophilic^{1st}$ – $Mesophilic^{2nd}$ OLR ND	Compared to that without recirculation, the system with recirculation was better at buffering and more stable in operation.	Ding *et al*., 2021
Vegetable waste	$CSTR^{1st}$ – Fixed-bed $reactor^{2nd}$ $Mesophilic^{1st}$ – $Mesophilic^{2nd}$ OLR 1.7 g-VS/(L.d)	The use of recirculation helped to improve mass transfer capacity between two-stage reactors.	Zuo *et al*., 2014
Potato-waste leachate	Fixed-bed $reactor^{1st}$ – Fixed-bed $reactor^{2nd}$ $Mesophilic^{1st}$ – $Mesophilic^{2nd}$ OLR of 12 g-COD/(L.d).	The bioreactor with a low recirculation flow rate showed operational stability.	Mshandete *et al*., 2004
BMSW	$CSTR^{1st}$ – $UASB^{2nd}$ $Mesophilic^{1st}$ – $Mesophilic^{2nd}$ OLR 4.0 g-VS/(L.d)	Increasing the yield of biogas and CH_4 concentration while stabilizing the hydrolysis process without the use of alkaline chemicals. The optimal methanogenic conditions were achieved with a TCOD of 35.2 g-O_2/L using the recirculation rate.	The current study

Notes: ^{1st} first reactor (fermentative reactor – FR); ^{2nd} second reactor (methane reactor – MR) in COD removal and biogas production, respectively. More details about the impact of effluent recycling on TAD systems with various biodegradable waste types are provided in Table 3.

From reactions (1) and (2), the decrease in CH_4 concentration brought on by the reduction in recirculation rate demonstrated that acetogenotrophic methanogens were more adapted to high substrate concentrations than hydrogenotrophic ones. Romli *et al*. (1994) stated that CH_4 content declined with increasing n value, which is the opposite of this conclusion. However, in their report, the pH of the influent was decreased from 7.6 to 6.6, accompanied by an increase in the recirculation rate. As discussed in the previous section, lowering the pH also led to a reduction in CH_4. As a result, the change in CH_4 demonstrated that the impact of lowering the pH was greater than the effect of increasing the recirculation rate. In particular, the significant linear correlation between the CH_4% obtained and the COD concentration of the influent suggested the sensitivity of the anaerobes in the up-flow reactor. This could be explained by the direct contact between obligate anaerobes and the high concentration of the substrates. It differs from a CSTR in that high substrate concentrations are immediately diluted by low substrate concentrations inside (Dinh *et al*., 2020). As a result, Cavinato *et al*. (2011) reported no significant influence of COD input ranging from 16 to 49 g-O_2/L on CH_4% while employing a CSTR for methanogenesis.

CONCLUSION

Anaerobic granular sludge has been proven to have great potential in treating high-concentration substrates such as BMSW. Although growing in the same reactor, the structure of granular sludge helps the methanogens, acidogens, and acetogens thrive much more than in suspended sludge. The relative abundance of methanogens in granular sludge (11.8%) was fivefold that obtained in suspended sludge (2.5%). In addition, the relative abundance of the acidogens/acetogens in granular sludge (37%) was significantly higher than that in suspended sludge (25%). Among methanogen families, *Methanobacteriaceae* was found to have the highest relative abundance (7.5% in granular sludge and 0.8% in suspended sludge). The formation of CH_4 mainly occurred in granular sludge via a dominant hydrogenotrophic pathway. Methane formation in suspended sludge occurred in a secondary manner, mainly via both the hydrogenotrophic and acetotrophic pathways. Methane synthesis by the methylotrophic methanogens in the reactor was not significant. Recirculating the effluent provided significant benefits, including the ability to stabilize the hydrolysis process and increase the methane yield. In the fermentative reactor, using the effluent stream to maintain a state of 12% total solids helped keep the reactor stable at pH 5.5 without alkali addition. In the case of using tap water for dilution, it required a NaOH dose of 115.8 g/kg-VS and 75.3 g/kg-VS to maintain pH conditions at 6.5 and 5.5, respectively. The concentration of fermentation products in the reactor maintained at pH 6.5 increased by 5.9% TCOD, 5.5% SCOD, and 10.6% VFAs in comparison with the reactor maintained at pH 5.5. In the case of recirculating the effluent stream in the methane reactor, increasing the dilution rate from 0.5 to 3.0 resulted in a CH_4 yield in the range of 227.5-278.9 mL/g-VS and COD removal in the range of 85-93%. The methane reactor's best digestion performance was attained at a recirculation rate of 2 to obtain influent with a TCOD of 35.2 g-O_2/L. The decline in CH_4 concentration following a decrease in pH or an increase in substrate concentration reflected that acetotrophic methanogens are better adapted to difficult conditions than hydrogenotrophic methanogens.

AUTHOR CONTRIBUTIONS

D.V. Pham performed the experiments, analyzed the data, and wrote the original draft. T. Fujiwara supervised the experiments. P. Astrini Notodarmojo helped to perform the experiments. K.C. Tran revised the manuscript.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percentage
°C	Degrees Celsius
AD	Anaerobic digestion
BMSW	Biodegradable municipal solid waste
C	Carbon
C/N	Carbon to nitrogen
CH_4	Methane
CO_2	Carbon dioxide
COD	Chemical oxygen demand
CSTR	Continuous stirred tank reactor
d	Day
DNA	Deoxyribonucleic acid
EDTA	Ethylenediaminetetraacetic acid
EX	Examination
Fig.	Figure
FR	Fermentative reactor
g/kg.VS	Gram per kilogram of volatile solids
$g\text{-}O_2/L$	Oxygen gram per liter
GS	Granular sludge
g-VS/(L.d)	Gram of volatile solids per liter per day
H_2	Hydrogen
M	Mole
mL/g.VS	Milliliter per gram of volatile solids
MR	Methane reactor
n	Recirculation rate for methanogenesis
N	Nitrogen
NaOH	Sodium hydroxide
pH	Potential of hydrogen
RT	Retention time
SCOD	Soluble chemical oxygen demand
SS	Suspended sludge
TAD	Two-stage anaerobic digestion
TCOD	Total chemical oxygen demand
TS	Total solid
UASB	Up-flow anaerobic sludge blanket
VFA	Volatile fatty acid

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SPECIAL ISSUE: Eco-friendly sustainable management
ORIGINAL RESEARCH PAPER

Using benthos a bioindicator to assess the efficiency constructed wetland community wastewater treatment system

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ABSTRACT

BACKGROUND AND OBJECTIVES: The increasing population and urban growth have led to a higher demand for water in various sectors, resulting in a significant amount of wastewater. Constructed wetlands mimic natural wetlands, using the interaction between plants, soil, and microorganisms to treat wastewater efficiently. This study assesses the diversity, species composition, and distribution of benthic organisms in a community wastewater-filter grass system and explores the relationship between water quality and benthos.
METHODS: Water samples were collected from plant plots between December 2021 and March 2022. On-site measurements included temperature, dissolved oxygen, salinity, and pH, whereas laboratory analysis encompassed the biochemical oxygen demand, ammonia, nitrate, total phosphorus, orthophosphate, and suspended solids. Soil samples were taken before and during planting at 2-week intervals, evaluating organic matter, pH, electrical conductivity, salinity, phosphorus, potassium, calcium, magnesium, and plant growth indicators. Benthos sampling involved polyvinyl chloride pipe cores at a depth of 5 cm from the soil surface. Statistical tests were performed to analyze the water quality data.
FINDINGS: The study observed a decrease in *Chironomid* abundance in both constructed wetland systems, indicating their effectiveness in treating wastewater. A comparison of system types revealed that the 5-day detention–2-day dry release system exhibited higher *Chironomid* abundance than the continuous flow system, and the biological oxygen demand maximum decreasing rate was 95%. The ammonia and nitrate maximum decreasing rates were 97% and 94%, respectively, indicating greater wastewater-treatment efficiency. The study also identified diverse benthic organisms, particularly chironomids, as bioindicators for assessing wastewater conditions.
CONCLUSION: The continuous flow system and the 5-day detention–2-day dry release system of constructed wetlands can reduce the organic compounds and increase the oxygen levels in the plant plots. The interaction among plants, soil, and microorganisms is critical in wastewater treatment. In addition, the study highlighted the diversity and abundance of benthic organisms, particularly chironomids, which were more prominent in the continuous flow system. Consequently, the 5-day detention–2-day dry release system was more efficient in treating wastewater than the continuous flow system.

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INTRODUCTION

The increasing population and urban growth cause a demand for water for domestic consumption, industries, and agriculture (Hoekstra and Chapagain, 2007; Bisselink *et al.,* 2018; Moghadam and Samimi, 2022; Nimesha *et al.,* 2022), causing a lot of wastewater. Human activities, such as washing, cooking, toilets, laundry, and others, cause municipal wastewater (Widyarani *et al*., 2022; Preisner, 2020; Fahad *et al*., 2019). Wastewater contaminates organic matter (OM) and inorganic matter (Hidayah *et al.,* 2022). Municipal wastewater has high nitrogen and phosphorus contents, causing eutrophication (Wang *et al*., 2012; Loomer *et al*., 2014; Ruiz *et al*., 2011; Piri and Sepehr *et al.,* 2022), which causes a lack of oxygen in the water. It increases aquatic plants (algal or plankton blooms), reduces the light intensity, and produces toxins that kill fish or other organisms that deoxygenate in the water (Muigai *et al*., 2010; Rabalais, 2002; Cahyonugroho *et al.,* 2022), affecting the water quality and environment. Wastewater treatment before releasing it into natural sources solves wastewater problems (Parvin *et al*., 2020). The treatment includes activated sludge, rotating biological contactor, and anaerobic filters (Gernaey *et al*., 2004; Waqas *et al*., 2021; Cortez *et al*., 2008; Samimi and Shahriari Moghadam, 2018; Dhayalan and Karuppasamy, 2021; Manjarrez Paba *et al.,* 2021), which are complicated, costly procedures and not ecofriendly (Kour *et al*., 2021). However, natural wastewater-treatment technology is easy and convenient. Constructed wetlands are similar to natural wetlands to mimic the wastewater-treatment mechanisms of existing wetlands (Haberl *et al*., 2003; Hunt *et al*., 1997). It takes advantage of the interaction between plants, soil, and microorganisms in wastewater treatment (Li *et al*., 2021; Hussain *et al*., 2018). The constructed wetland is a popular biological wastewater-treatment system due to its low cost and energy. It is efficient for treating suspended solids (SS), the chemical oxygen demand, the biological oxygen demand (BOD), nutrient nitrogen (N), and phosphorus (P) (Mantovi *et al*., 2003; Rousseau *et al*., 2004 ; Samimi and Shahriari Moghadam, 2020) by microorganisms in the root. Bacteria are crucial in decomposing OM by nitrification and denitrification, and the transformation of nitrogen and phosphorus comes from the microbial activity in the root area (Cui *et al*., 2013; Hu *et al*., 2023). The tolerance of hypertrophic waterlogged plants and their ability to remove pollutants should be considered (Scholz and Lee, 2005). Wetland ecosystems can increase biodiversity and be nutrient traps, contributing to high bird biodiversity benthos and macrophytes (Hansson *et al*., 2005). Benthos is a biomarker to assess ecosystem health (Kelly *et al*., 2017). This research studies the diversity, species, proportion, and distribution of benthos and finds the relationship between the water quality and benthos in the community wastewater-filter grass system. This study was conducted in the constructed wetland community wastewater-treatment system at the King's Royally Initiated Laem Phak Bia Environmental Research and Development Project (LERD), in Phetchaburi, Thailand, from 2021 to 2022.

MATERIALS AND METHODS

Study site

Constructed wetland is located at the King's Royally Initiated Laem Phak Bia Environmental Research and Development Project (The LERD

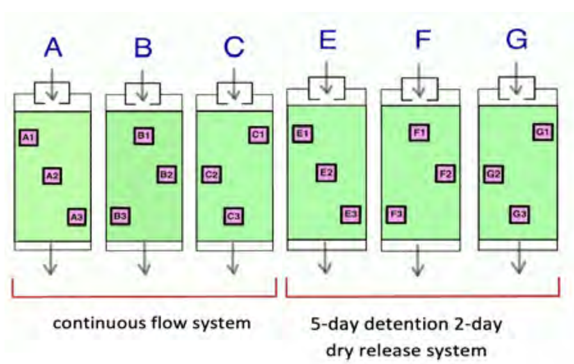

Fig. 1: Sample plant plots

(a) (b)

Fig. 2: Constructed wetland system (a) continuous flow system and (b) 5-day detention–2-day dry release system

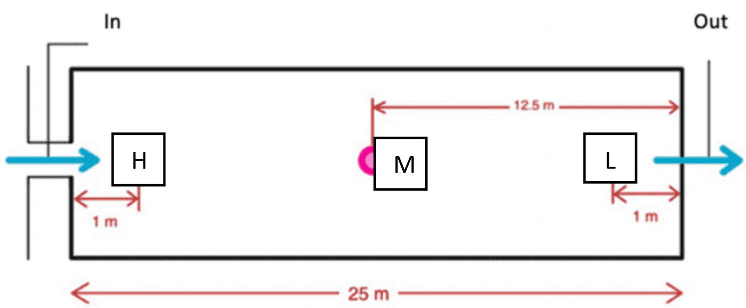

Fig. 3: Soil and benthos sampling point

project), Phetchaburi, Thailand. The treatment system consists of six constructed wetland plots (Fig. 1). using *Phragmites australis*. Community wastewater was discharged from the municipality of Phetchaburi into the plots in the continuous flow system (Fig. 2a). and 5-day detention 2-day dry release system (Fig. 2b). The treatment system consists of six constructed wetland plots, each measuring 5x25x1.5 meters (width x length x depth) and filled with a layer of gravel (30 centimeter: cm), sand (20 cm), soil (30 cm), and a 30 cm high water level. The plots were planted with small reed (*Phragmites australis Cav*.) with a planting distance of 40x40 cm and nine plants per square meter. Community wastewater was discharged from the municipality of Phetchaburi into the plots in a detention-dry release system (5-day detention and 2-day dry release system), and the flow was continuous for six study plots. Plots A to C were operated in the continuous flow system, while plots E to G were operated in 5-day detention 2-day dry release system. Water, soil, and benthos samples were collected at three monitoring stations located at 0 m, 12.5 m, and 25 m distances from the inflow point.

Water sample analyses

The water samples in the plant plots were collected and analyzed from December 2021 to March 2022 (10 weeks). Four water quality parameters were measured on-site: temperature (temp), dissolved oxygen (DO), salinity, and potential hydrogen (pH). Six parameters were measured in the laboratory: BOD, total nitrogen (TN), total kjeldahl nitrogen (TKN), ammonia (NH_3), nitrate (NO_3^-), total phosphorus (TP), orthophosphate (OP), phosphate (PO_4^{3-}), and SS were evaluated according to the standard methods for examining water and wastewater (APHA, 2005).

Soil and plant analyses

Take a soil sample before and during planting every 2 weeks. Soil quality parameters were measured as OM, pH, electrical conductivity (EC), salinity, phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) at the head (H), middle (M), and last (L) of the plot (Fig. 3) and plant growth, such as plant height and circumference, was studied.

Benthos sampling

Benthos was sampled using a polyvinyl chloride (PVC) pipe (core), eight inches in diameter, sampled down to 5 cm height from the soil surface at the head (H), middle (M), and last (L) of the plot (Fig. 3). Fixed with 7% formalin and fined benthos species. Cell counting was conducted in a laboratory. The diversity indices were calculated using the Shanon–Weiner Index method.

Statistical analysis

Statistical analysis was performed using the statistical package for social sciences to analyze the water quality data. Descriptive statistics were calculated for all parameters, and inferential statistics, such as *t*-tests or analysis of variance, were conducted to assess differences between system types and time points. Regression analysis was used to explore the relationship between water quality variables and benthic organism diversity. The statistical significance was set at $p < 0.05$.

RESULTS AND DISCUSSION

Water quality

The continuous flow and 5-day detention–2-day dry release systems at H, M, and L of the plot have different treatment efficiencies and water qualities. The average temperature, pH, BOD, TP, and DO in the continuous flow and 5-day detention–2-day dry release systems were equal to the standard values. The average DO, SS, and NO_3^- increased, whereas the average BOD, NH_3, TKN, TN, TP, and PO_4^{3-} decreased (Tables 1 to 3). The BOD decreased because the increased oxygen in the two constructed wetlands was enough for microorganisms to oxidize the organic compounds in wastewater (Prihatini *et al*., 2019). The average NO_3^- concentration increased while the average NH_3 concentration decreased. The removal of NH_3 was primarily due to the increasing nitrification process and the growth of nitrification bacteria that converted nitrogen from NH_3 to NO_3^-. Consequently, the nitrate concentration increased and NH_3 decreased in the constructed wetland

Table 1: Water quality of continuous flow and 5-day detention–2-day dry release systems

Parameters	Continuous flow system			Average	5-day detention–2-day dry release system			Avg.
	H	M	L		H	M	L	
Temp. (°C) (23-32[2])*	26.97	26.79	26.63	26.80	26.29	26.35	26.23	26.28
pH (5.5-9.0[1])*	7.58	7.61	7.64	7.61	7.75	7.75	7.79	7.76
DO (mg/L) (>3[2])*	1.20	2.09	2.94	2.08	5.88	5.66	6.54	6.02
BOD (mg/L) (<20[1])*	11.57	11.05	6.78	9.80	8.51	5.87	7.97	7.45
SS (mg/L)	18.70	16.87	21.60	19.06	26.07	26.20	30.63	27.62
NO_3^- (mg/L)	0.06	0.06	0.11	0.08	0.17	0.12	0.24	0.18
NH_3 (mg/L)	1.44	1.27	1.15	1.29	0.93	0.77	0.56	0.76
TKN (mg/L)	4.87	4.67	3.51	4.35	3.36	2.94	2.75	3.02
TN (mg/L)	4.87	4.67	3.51	4.35	3.36	2.94	2.75	3.02
TP (mg/L) (<2[1])*	1.00	1.07	0.95	1.01	1.00	0.66	0.78	0.81
OP (mg/L)	1.77	1.67	1.63	1.69	1.09	1.03	0.87	0.99

[1] The water quality standard of control drains effluent water from the community wastewater-treatment system from the Ministry of Natural Resources and Environment, Thailand.

[2] The water quality standard of water quality for aquatic animal life from the Department of Fisheries, Thailand.

Table 2: Treatment efficiency of the continuous flow system (%)

Week	BOD	SS	FOG	TN	NO_3^-	NH_3	TP	PO_4^{3-}
1	31.36	33.33	95.29	24.53	54.62	53.73	14.81	9.78
2	46.08	−91.30	95.51	49.15	7.14	60.24	13.07	26.22
3	88.78	−42.31	98.48	45.39	88.07	86.16	42.08	16.67
4	38.46	13.33	83.24	36.60	35.74	50.80	15.68	9.39
5	49.93	68.42	52.65	45.10	72.09	17.02	13.31	2.93
6	75.96	−5.88	46.58	55.12	94.83	89.67	22.47	14.60
7	66.35	75.00	67.00	50.64	7.69	49.69	44.27	34.43
8	83.33	−166.67	99.99	13.74	95.79	82.52	11.96	11.71
9	56.16	42.11	97.03	12.86	99.35	56.44	18.59	39.00
10	54.10	33.33	36.00	38.42	1.06	79.33	4.21	4.76

Table 3: Treatment efficiency of the 5-day detention–2-day dry release system (%)

Week	BOD	SS	FOG	TN	NO_3^-	NH_3	TP	PO_4^{3-}
1	60.10	62.50	92.75	24	79.57	83.79	60.96	75.20
2	31.42	−667.86	95.69	7.49	85.00	78.72	54.61	64.17
3	95.06	−290.00	90.97	9.97	39.33	65.63	63.33	54.05
4	16.58	17.39	24.21	6.57	67.91	79.88	61.56	70.32
5	58.16	32.26	15.12	5.08	85.58	88.61	66.38	67.29
6	79.38	20.00	17.72	7.57	74.82	97.13	66.84	67.23
7	6.77	−81.16	69.44	4.23	40.00	38.80	47.31	37.95
8	55.37	−141.67	99.96	1.03	94.35	92.50	55.59	19.39
9	50.18	−18.18	96.99	2.39	56.08	84.61	49.92	48.98
10	63.46	55.56	74.70	35.78	19.32	11.87	32.38	3.23

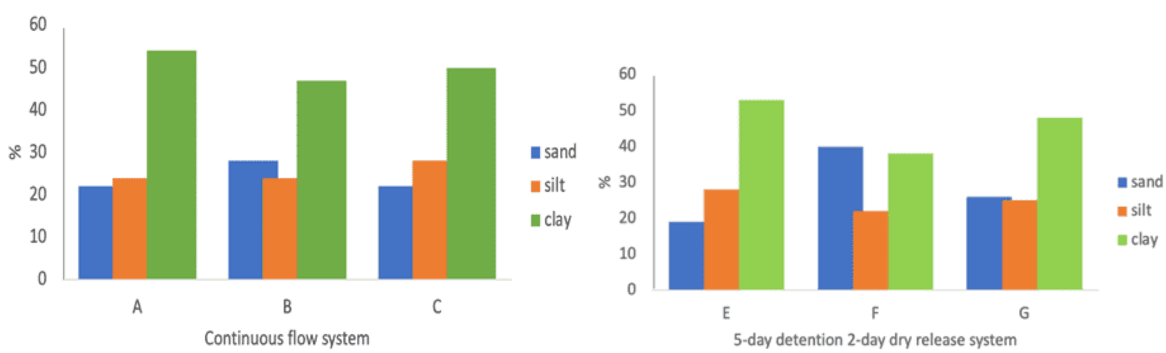

Fig. 4: Soil content in the constructed wetlands

(Jamieson *et al.*, 2003). The phosphorus nutrient concentration (TP and OP) decreased and conversed by uptake, precipitation, and assimilation into microbial and plant biomass in the plots (Kouki *et al.*, 2009).

Soil and plant

The soil content was classified by the percentage of sand (%sand), percentage of silt (%silt), and percentage of clay (%clay). Three constructed wetlands were compared (A/E, B/F, and C/G). The soil content was clay (>38%), sand (>24%), and silt (>25%) (Fig. 4). Soil texture in the continuous flow system A comprised clay, followed by clay loam, whereas E of the 5-day detention–2-day dry release system comprised clay followed by silty clay. B in the continuous flow system contained clay, followed by clay loam, whereas F of the 5-day detention–2-day dry release system mostly was clay, followed by clay loam, sandy loam clay, and silt loam. C of the continuous flow system was clay, followed by silty clay, whereas G of the 5-day detention–2-day dry release system contained clay, followed by clay silty, silty clay loam, and clay loam.

Fig. 5: Plot of *Phragmites australis*

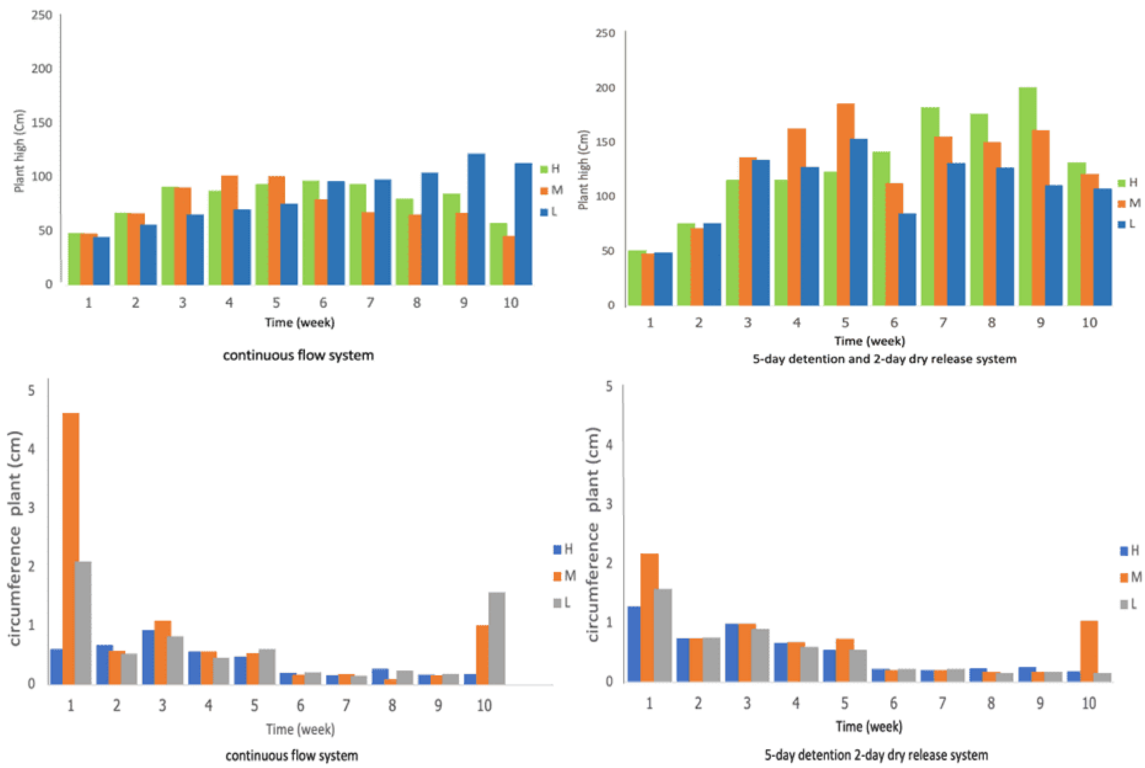

Fig. 6: High and circumference of *Phragmites australis*

Plant plots of wastewater-treatment systems using Phragmites australis

The plant plots of the wastewater-treatment system using *Phragmites australis* are shown in Fig. 5:

(a) Nursery plant plot, (b) Nursery plant plot, (c) Plant plot continuous flow system, (d) Plant plot 5-day detention–2-day dry release system, (e) Stem of *Phragmites australis*, (f) Stem of *Phragmites australis,* (g) Flower of *Phragmites australis*, (h) Flower of *Phragmites australis*, (j) Flower of *Phragmites australis*.

The plant growth measurements include the height and circumference of *Phragmites australis*. The height and circumference of plants increased from week 1 to week 10. Comparing the two constructed wetland systems showed that the 5-day detention–2-day dry release system plants grew better than the continuous flow system (L, H, and H, respectively). However, the plant circumference decreased from week 1 to week 10. The continuous flow system plant circumferences were 4.64–1.01 cm (M), 2.1–1.58 cm (L), and 0.61–0.19 cm (H), and the 5-day detention–2-day dry release system delivered 2.18–1.04 cm (M), 1.58–0.16 cm (L), and 1.29–0.18 cm (L) (Fig. 6).

Benthos

The benthos species diversity and abundance in the constructed wetlands found two phyla, two classes, and seven species comprising one species of *Phylum Annelida* and six of *Phylum Arthropoda*. *Phylum Arthropoda* and *Annelida* were higher in the 5-day detention–2-day dry release system than in the continuous flow system. The 5-day detention–2-day dry release system has a higher benthos species diversity and abundance than the continuous flow system (Table 4).

Benthos can be used as a wastewater indicator for environmental or water quality assessment because they are sedentary and play a role in cycling nutrients (Carretero *et al*., 2016). Tubifex worms are known for tolerating polluted and oxygen-depleted waters (Hurley *et al*., 2017). They are frequently found in sediments and can feed on OM, including wastewater

Table 4: Benthos species diversity and abundance in the constructed wetlands

Benthos	Constructed wetlands					
	Continuous flow			5-day detention–2-day dry release		
	A	B	C	E	F	G
Phylum Annelida						
Class Oligochaeta						
Order Plesiopora						
Family Tubificidae						
Tubifex sp.	51	33	45	481	58	471
Phylum Arthropoda						
Class Insecta						
Order Diptera						
Family Chironomidae						
Ablabesmyia sp.	66			22	88	
Chironomus sp.	83	381	22	88		37
Pseudosmittia sp.	44	455	270	66	577	46
Family Ceratopogonidae						
Culicoides sp.			33	22		79
Order Hemiptera						
Family Corixidae						
Corisella sp.	37	26	44	88	108	62

pollutants. However, their role in contaminant removal from wastewater is more related to OM decomposition and nutrient cycling than direct pollutant removal. *Ablabesmyia* larvae are aquatic midges typically found in freshwater habitats. They play a role in wastewater treatment by consuming OM, including bacteria and other microorganisms, in the wastewater, reducing the organic load and improving water quality (Rae, 1989). *Pseudosmittia* larvae are part of the nonbiting midge family in various freshwater environments and contribute to the decomposition of OM, including wastewater contaminants. While they might not have specific pollutant removal mechanisms, their feeding habits and role in nutrient cycling indirectly improve the water quality. *Culicoides*, commonly known as biting midges, are not typically associated with wastewater treatment and are more commonly known as vectors for diseases in animals, and their presence in wastewater might not contribute significantly to contaminant removal. *Corisella* are small aquatic beetles found in freshwater environments. They feed on OM, including detritus and microorganisms, and contribute to the breakdown of pollutants in the wastewater. However, their overall impact on wastewater is limited compared to other species specifically adapted to such environments. *Chironomus* larvae, also known as bloodworms, are frequently found in polluted and eutrophic waters and are effective in organic pollutant removal. *Chironomus sp*. has been used in constructed wetlands and wastewater-treatment systems to enhance OM degradation and pollutant removal. In summary, the *Chironomus sp*. and *Ablabesmyia sp*. in the family *Chironomidae* show more potential for wastewater treatment due to their ability to consume OM and contribute to pollutant removal. Therefore, the family *Chironomidae* was a bioindicator used to assess pollution in aquatic ecosystems. They are strongly related to ammonium-N and are the highest pollution (Akyildiz *et al*., 2018). The density of the family *Chironomidae* in the wetlands decreased from week 1 to week 10 and was not found at week 9 because of the lower OM (Carretero *et al*., 2016). The *Chironomidae* in the continuous flow system and the 5-day detention–2-day dry release system was compared, showing that *Chironomidae* was higher in the continuous flow system than the 5-day detention–2-day dry release system (Fig. 7) because NH_3 in the continuous flow system is higher (Table 1). The decreasing *Chironomidae* in both constructed wetland systems showed that the wastewater-treatment system is effective for treating wastewater. Comparing the system types showed that the continuous flow system has higher

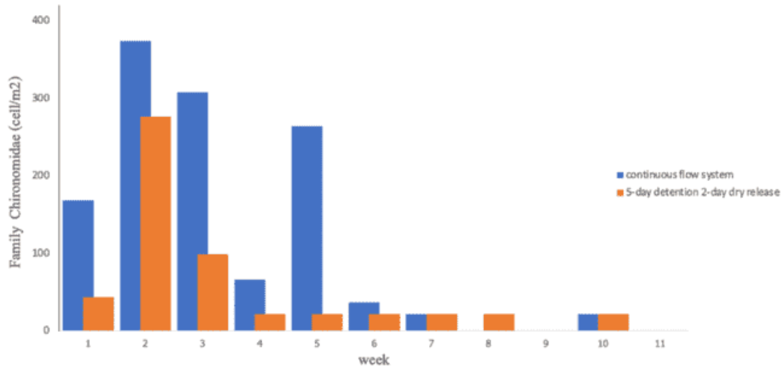

Fig. 7: Density of the family *Chironomidae* in the constructed wetlands

Table 5: Statistical testing of water quality in the wastewater-treatment systems

Parameters	Continuous flow		5-day detention–2-day dry release		*t*-test	Sig.
	Mean	SD	Mean	SD		
Temp	26.74	1.738	26.20	1.961	1.377	0.172
pH	7.63	0.560	7.91	0.695	−2.087	0.040
EC	523.22	35.810	526.58	39.540	−0.422	0.674
DO	2.41	2.155	4.81	2.860	−4.493	0.000
BOD	13.20	14.533	8.68	12.740	1.569	0.120
TP	1.20	0.203	0.61	0.164	14.993	0.000
PO_4^{3-}	2.03	0.325	1.05	0.396	12.913	0.000
SS	15.91	9.660	23.84	12.244	−3.412	0.001
NO_3^-	−0.03	0.403	0.07	0.477	−1.055	0.294
NH_3	1.07	0.705	0.47	0.374	5.106	0.000
TKN	4.37	1.716	2.59	1.130	5.816	0.000
Salinity	0.20	0.000	0.20	0.000	0.000	1.000

Chironomidae than the 5-day detention–2-day dry release system, showing it was more wastewater treatment efficient than the continuous flow system.

Statistics

The statistical water quality testing of two constructed wetlands was the independent sample *t*-test and showed that the temp., EC, BOD, and salinity have Sig greater than 0.05, indicating that the wastewater-treatment systems were not significantly different. The wastewater-treatment systems can reduce organic compounds to decrease the BOD (Charkhestani and Yousefi Kebria, 2022). While the pH, DO, TP, OP, SS, NH_3, and TKN lower than 0.05 indicate that the wastewater-treatment systems differed significantly (Table 5).

Table 6: Statistical testing of soil properties in the wastewater-treatment systems

Parameters	Continuous flow		5-day detention–2-day dry release		*t*-test	Sig.
	Mean	SD	Mean	SD		
OM (%)	2.06	0.386	2.29	0.386	−2.928	0.004
EC (µS/cm)	177.83	66.666	296.61	123.147	−5.690	0.000
pH	8.33	0.492	7.87	0.543	4.219	0.000
Salinity (dS/m)	0.18	0.067	0.30	0.123	−5.690	0.000
Avail. P (mg/kg)	13.86	3.026	17.78	5.044	−4.478	0.000
K (mg/kg)	164.75	75.219	165.30	73.391	−0.035	0.972
Ca (mg/kg)	658.66	224.510	694.35	198.549	−0.799	0.427
Mg (mg/kg)	172.32	196.088	141.08	146.472	0.856	0.394

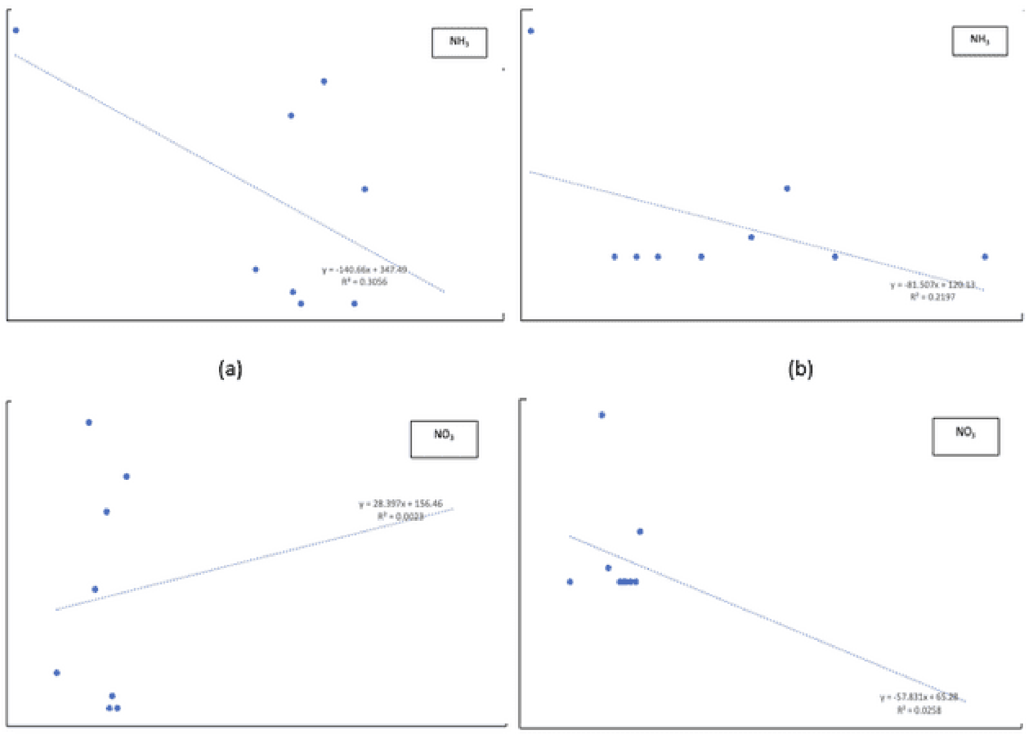

Fig. 8: Correlation between the family *Chironomidae* and N nutrients
(a) Correlation between the family Chironomidae and NH_3 in the continuous flow system
(b) Correlation between the family Chironomidae and NH_3 in the 5-day detention–2-day dry release system
(c) Correlation between the family Chironomidae and NO3 in the continuous flow system
(d) Correlation between the family Chironomidae and NO3 in the 5-day detention–2-day dry release system

K has a significance greater than 0.05 in the soil properties, indicating that the wastewater-treatment systems were not significantly different. OM, EC, pH, salinity, avail. P, Ca, and Mg were lower than 0.05, indicating that the wastewater-treatment systems differed significantly (Table 6).

The major elements (P, K, Ca, and Mg) in the soil are critical for plant growth. If they are lacking, normal development does not occur. P and Ca in the 5-day detention–2-day dry release system is higher than in the continuous flow system, causing the plants in the 5-day detention–2-day dry release system to be higher than in the continuous flow system.

Benthos and nutrients

Benthos (family *Chironomidae*) and nutrients, such as NH_3 and NO_3^- were used to analyze the relationship shown in Fig. 8. The relationship between benthos and NH_3 and benthos and NO_3 were compared in the continuous flow and 5-day detention–2-day dry release systems. The results showed that benthos has a higher correlation with NH_3 than NO_3, and the continuous flow system has a higher correlation between benthos and the continuous flow system than the 5-day detention–2-day dry release system. Therefore, the family *Chironomidae* has a better relationship with NH_3 and the continuous flow system.

CONCLUSIONS

The constructed wetlands of the continuous flow and 5-day detention–2-day dry release systems can reduce the organic compounds, BOD, NH_3, TN, TP, and PO_4^{3-} by 95%, 97%, 35%, 67%, and 75%, respectively. However, the BOD is higher than the wastewater-treatment standard (<20 mg/L), while SS increased by 68% and the DO rate increased from 5.88 to 6.54 mg/L, showing that this wastewater-treatment system can increase oxygen into the plant plots. The wastewater-treatment mechanism is the interaction between plants, soil, and microorganisms in the plots. Moderate OM and pH of soil occurred in the system, and the *Phragmites australis* height increased. Furthermore, the benthos diversity and abundance in the constructed wetland systems, especially *Chironomidae*, were bioindicators used to assess wastewater. The average NO_3^- concentration increased while the average NH_3 concentration decreased. The removal of NH_3 was primarily due to the increasing nitrification process and the growth of nitrification bacteria that converted nitrogen from NH_3 to NO_3^-. Consequently, the nitrate concentration increased and NH_3 decreased in the continuous flow system. Benthos can be used as a wastewater indicator for environmental or water quality assessment because they are sedentary and play a role in cycling nutrients. *Chironomidae* was a bioindicator used to assess pollution in aquatic ecosystems. They are strongly related to ammonium-N and are the highest pollution in the continuous flow system. Therefore, the 5-day detention–2-day dry release system is more efficient in treating wastewater than the continuous flow system. *Chironomidae* has been the focus of extensive research due to their significant role in sediment–water interactions. These have been found to influence the movement of N compounds across the sediment–water interface. The results show that *Chironomidae* can enhance the release of ammonium to 97% from the sediment into the overlying water, thereby increasing its availability. However, contrasting findings have also been reported, proposing that *Chironomid* larvae can have the opposite effect on nitrogen dynamics. Specifically, this study has shown that *Chironomidae* increases the release rates of nitrate nitrogen to 94%, indicating that the presence of *Chironomidae* can influence the release of different forms of inorganic nitrogen, depending on the specific environmental conditions and factors at play. The influence of Chironomidae on the exchange of inorganic nitrogen is yet to be fully understood and might be subtle. The effects can vary depending on sediment characteristics and the availability of OM. In summary, *Chironomidae* has garnered significant attention in research primarily due to their involvement in sediment–water interactions. They have been found to affect the outflow of nitrogen compounds, including ammonium and nitrate, across the sediment–water interface. However, the exact nature of their impact on nitrogen dynamics remains complex and context-dependent, necessitating further investigation.

AUTHOR CONTRIBUTIONS

K. Seethong designed the experiment, conducted field study water quality analyses in the laboratory, contributed in the data analysis, interpreted the results and preparing the manuscript. K. Chunkao participated in the interpretation of the wáter quality results and manuscript preparation. N. Dampin contributed in the benthos data analysis and interpretation of the results. W. Wararam, the corresponding author, has contributed in supervising the second author in the data analysis wáter quality and benthos, interpreted the results.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

ABBREVIATIONS

%	Percent
°C	Degree Celsius
µS/cm	MicroSiemens per centimeter
dS/m	DeciSiemens per meter
Avail. P	Avaiable phosphorus
APHA	American Public Health Association
BOD	Biological oxygen demand
cm	Centimeter
Ca	Calcium
COD	Chemical oxygen demand
DO	Dissolved oxygen
EC	Electrical conductivity
H	Head of plant plot
K	Potassium
km	Kilometer
L	Last of plant plot
LERD	the King's Royally Initiated Laem Phak Bia Environmental Research and Development Project
m	Meter
M	Middle of plant plot
Mg	Magnesium
mg/kg	Milligrams per kilograms
mg/L	Milligrams per liters
NH_3	Ammonia
NO_3^-	Nitrate
OP	Orthrophosphate
OM	Organic matter
pH	Potetial of hydrogen
PO_4^3	Phosphate
PVC	Polyvinyl chloride
Sp.	Specie
SS	Suspended solid
Temp	Temperature
TKN	Total kjedahl nitrogen
TP	Total phosphorus

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SPECIAL ISSUE: Eco-friendly sustainable management
ORIGINAL RESEARCH PAPER

Sustainable development model toward environmentally friendly hospital

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ABSTRACT

BACKGROUND AND OBJECTIVES: This study aims to create an environmentally friendly hospital at West Pasaman regional public hospital by implementing a sustainable development model, which consists of the green hospital, green building, green innovation, and green human resource management. The researchers previously discussed the physical aspects of the building, efficiency related to energy saving and hospital waste management. However, from several references obtained, it has not yet been discussed what is the extent of the benefits derived from the entire implementation of the green hospital. Thus, this study contributes to creating an environmentally friendly hospital model mediated by a green hospital and it is influenced by green building, green innovation, and green human resource management.
METHODS: The study method uses a survey, which uses a questionnaire as a data collection tool. The population in this study consisted of employees, visitors, and the community around West Pasaman regional public hospital. The selection of the sample in this study was based on the proportionate cluster random sampling approach, which was analyzed using the structural equation modeling–partial least square method.
FINDINGS: There are ten findings for analysis at the West Pasaman regional public hospital. First, green building has a significant effect of 0.187 on the green hospital. Second, green innovation has a significant effect of 0.230 on the green hospital. Third, green human resource management has a significant effect of 0.235 on the green hospital. Fourth, green building has a significant effect of 0.263 on the environmentally friendly hospital. Fifth, green innovation has a significant effect of 0.192 on the environmentally friendly hospital. Sixth, green human resource management has a significant effect of 0.197 on the environmentally friendly hospital. Seventh, the green hospital has a significant effect of 0.241 on the environmentally friendly hospital. Eighth, green building has a significant effect of 0.045 on the environmentally friendly hospital mediated by the green hospital. Ninth, green innovation has a significant effect of 0.055 on the environmentally friendly hospital mediated by the green hospital. Tenth, green human resource management has a significant effect of 0.057 on the environmentally friendly hospital mediated by the green hospital.
CONCLUSION: Implementation of the sustainable development model as a form of environmental management policy at the West Pasaman regional public hospital is optimally needed in order to achieve an environmentally friendly hospital. This study recommends employees, visitors the community around the West Pasaman regional public hospital to increase the green hospital, green building, green innovation, and green human resource management in achieving an environmentally friendly hospital.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
58	1	7

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INTRODUCTION

An environmentally friendly hospital (EFH) is a concept of implementing activities in a hospital that prioritizes public health by continuing to reduce environmental impacts and eliminate their damaging effects (Gao *et al.,* 2016). There are several key components of a sustainable development model to create EFH (Li *et al.,* 2013). First, life cycle costs and environmental impact, which is achieved through energy life cycle analysis of zero energy buildings including renewable energy. This involves an energy life cycle accounting technique for assessing the energy efficiency and emission implications of either a building or a particular renewable energy technology; Second, climate change, where recent reviews of the impact of climate change on the energy sector in particular have highlighted the vulnerability of energy systems and buildings to climate change (Puno *et al.,* 2021; Asnawi *et al.,* 2022); Third, and which is important for monitoring the impact of energy policy in the social, economic, and environmental dimensions, social policy issues related to energy as a key component in the overall strategy for sustainable development (Drobyazko *et al.,* 2021; Moghadam and Samimi, 2022; Ramli *et al.,* 2022). However, the existing hospital actually contributes a lot of waste to the environment because this waste is often disposed of freely without proper management, such as uncontrolled burning and irresponsible burial (Bucătaru *et al.,* 2021). Furthermore, attracting the attention of the world community because it is in line with the issue of global warming, which is caused by the negative contributions of buildings, such as water and electricity consumption, carbon footprint emission and waste disposal (Thiel *et al.,* 2017), the use of energy in hospitals is still inefficient, thus making it a contributor to environmental damage (García-Sanz-Calcedo *et al.,* 2019; González *et al.,* 2018; Vourdoubas, 2018). Business or building owners tend to be reluctant to implement it because it is difficult to apply green principles, including to hospitals because the initial investment costs are higher (Shabaani *et al.,* 2016). This research refers to several relevant articles to find out the state-of-the-art of our studies, including by Hwang and Tan (2012) analyzing green building (GB) for sustainable development. Here, they found that government incentives are needed to overcome obstacles to implementing GB, such as the use of green products and technology. Then, a more specific study was conducted by Azar *et al* (2015), in which they evaluated green hospital (GH) in teaching and private hospitals covered by Tehran University of Medical Sciences. The results of the study found that, compared to government hospitals, private hospitals scored higher on all aspects of GH apart from management and leadership, but there was no statistically significant difference between dimensions and type of hospital in government and private hospitals, because the hospitals studied did not fulfill GH well. Furthermore, this study is expanded by Khan and Zubair (2019) in their study, in which they propose that sustainable adoption and environmentally friendly practices are needed in organizations in the form of green human resource management (GHRM) and which involves the role of GHRM in achieving sustainable development. On the other hand, Khan *et al.* (2021) analyzed the adoption of Organisasi Standardisasi Internasional (ISO) 56002-2019 and green innovation (GI) reporting enhance the firm's sustainable development goal performance, in which they found that GI will increase business transparency due to the development of sustainable corporate goal performance. In addition, Benzidia *et al.* (2021) conducted a recent study on green supply chain process integration and EFH, which provides valuable insights for managers in improving environmental performance. Based on explanations from various empirical phenomena that studies on environmental management for hospitals are still limited and that the concept of EFH, which is driven by the sustainable development model, still tends to be ignored, this research will fill this void by involving the roles of GH, GB, GI, and GHRM adopted from previous research variables as components of the sustainable development model to achieve EFH. Hospitals can adopt EFH and sustainable supply practices to support sustainable goals through the involvement of a green physical and nonphysical environment because it requires support from all aspects. The physical environment consists of GB and GH. Meanwhile, the nonphysical environment consists of GI and GHRM. West Pasaman Regional Public Hospital (WPRPH) is one of the hospitals that is working toward EFH. However, the phenomenon that has occurred for the implementation of GB so far is that, because in making the nonoptimal initial master plan, it conditioned the existing buildings and adjusted them to the continuity of services by using existing infrastructure, the implementation of this master plan is flawed because the development of the land is still not quite right.

Table 1: Research population

Population	Total
WPRPH employees	536
WPRPH visitors	38.158
community around WPRPH	57

Furthermore, the phenomenon that has occurred for the implementation of GI so far is that medical waste has increased over the past five years, which requires GI efforts to overcome this increase so that it can be reused. Besides that, the phenomenon that has occurred for the implementation of GHRM so far is that they have not implemented special training related to environmentally friendly attitudes, such as green compensation. In particular, this study has explored relevant literature studies regarding the concept of sustainable development, which consists of GH, GB, GI, and GHRM to achieve EFH as a solution to problems that occur in WPRPH, which is based on what factors encourage or hinder this implementation. Based on explanations from various empirical phenomena and facts, the study aims are as: 1) Investigate the effect of GB, GI and GHRM on GH; 2) Investigate the effect of GB, GI, GHRM and GH on EFH; 3) Investigate whether GH is able to mediate between GB, GI, and GHRM to EFH. This study was conducted at the West Pasaman Regional Public Hospital in Indonesia in 2022.

MATERIALS AND METHODS

Data types and sources

The type of data used in this study is quantitative, the data obtained from distributing questionnaires to employees, visitors, and the community around WPRPH from May to December 2022. Then, the data source used in this study is primary data, which uses a questionnaire distributed to respondents as measured by a Rating scale (1–5).

Data collection

The population in this study refers to several data sources, including WPRPH employees, WPRPH visitors, and the community around WPRPH, which is summarized in Table 1.

Based on the information in Table 1, the sampling technique used is proportionate cluster random sampling, which pays attention to the sample area of the population elements. Furthermore, to determine the sample size in this study using the Slovin in Eq. 1 (Tejada and Punzalan, 2012).

$$n = \frac{N}{1 + Ne^2} \quad (1)$$

Where; n = Sample size, N = Population size, e^2 = 10% error

First, the selection of samples for WPRPH employees was determined using several criteria, including employees with casual daily worker status, regional honorarium, and civil servants; has a working period of more than 4 years; minimum high school education for management staff and functional staff; and minimum postgraduate education for field heads and section heads. Based on these various criteria, the number of samples for WPRPH can be seen in Eq. 2 (Tejada and Punzalan, 2012).

$$n = \frac{536}{1 + 536\,(0{,}1)^2} = 84.27\text{, then set to 84 employees} \quad (2)$$

Based on the calculation of the number of samples at in Eq. 2, the characteristics of the respondents for WPRPH employees can be seen in Table 2.

Based on Table 2, it can be explained that the distribution of the number and percentage of respondents is for WPRPH employees. First, female employees respond more to efforts to achieve EFH. Second, employees aged 36–45 years respond more to efforts to achieve EFH. Third, employees with postgraduate education respond more to efforts to achieve EFH. Fourth, employees who have income >235 USD/month respond more to efforts to achieve EFH. Fifth, employees who have worked for 10–19 years respond more to efforts to achieve EFH. Further, the selection of samples for WPRPH visitors was determined using several criteria, including visitors having a minimum age of 25 years; visitors have visited more than twice in 2021; and visitors have at least high school education. Based on these various criteria, the number of samples for year WPRPH visitors can be seen in Eq. 3 (Tejada and Punzalan, 2012).

$$n = \frac{38.158}{1 + 38.158\,(0{,}1)^2} = 99.73\text{, then set to 100 visitors} \quad (3)$$

Table 2: Characteristics of WPRPH employees

Characteristics	Option	Achievements	
		Frequency (Person)	Percent (%)
Gender	Man	21	25
	Woman	63	75
Age	26–35 years	19	22.6
	36–45 years	48	57.1
	46–55 years	17	20.2
Education	Senior high school	4	4.8
	Diploma	20	23.8
	Bachelor	26	31.0
	Postgraduate	34	40.5
Income	<100 USD/month	12	14.3
	100–165USD/ month	6	7.1
	166 –235 USD/ month	13	15.5
	>235 USD/ month	53	63.1
Length of work	≤4 years	11	13.1
	5–9 years	27	32.1
	10–19 years	45	53.6
	≥20 years	1	1.2

Table 3: Characteristics of WPRPH visitors

Characteristics	Option	Achievements	
		Frequency (Person)	%
Gender	Man	52	52
	Woman	48	48
Age	25–35 years	32	32
	36–45 years	32	32
	46–55 years	34	34
	55–65 years	2	2
Education	Senior high school	76	76
	Diploma	8	8
	Bachelor	14	14
	Postgraduate	2	2
Income	<100 USD /month	29	29
	100–235 USD/ month	60	60
	>235 USD/ month	11	11
Number of visits	≤2 times	9	9
	3–5 times	49	49
	6–10 times	24	24
	≥10 times	18	18

Based on the calculation of the number of samples at Eq. 3, then the characteristics of the respondents for WPRPH visitors can be seen in Table 3.

Based on Table 3, the distribution of the number and percentage of respondents for WPRPH can be explained. First, male visitors respond more to efforts to achieve EFH. Second, visitors aged 46–55 years respond more to efforts to achieve EFH. Third, visitors with senior high school education respond more to efforts to achieve EFH. Fourth, visitors who have an income of 100–235 USD/month respond more to efforts to achieve EFH. Fifth, visitors who have visited 3–5 times respond more to efforts to achieve EFH. Third, the selection of samples for the community around WPRPH is determined using several criteria: These include people who live around a radius of 50 meters in the WPRPH environment and who have lived for more than one year; people who are at least 25 years old; the community has at least a senior high school education; and the public who know about the WPRPH environment. Based on previous information, the total population for the community around

Table 4: Characteristics of communities around WPRPH

Characteristics	Option	Achievements	
		Frequency (Person)	%
Gender	Man	28	49.1
	Woman	29	50.9
Age	25–35 years	15	26.3
	36–45 years	38	66.7
	46–55 years	4	7
Education	Senior high school	45	78.9
	Diploma	3	5.3
	Bachelor	7	12.3
	Postgraduate	2	3.5
Income	<100 USD /month	20	35.1
	100–235 USD/ month	33	57.9
	>235 USD/ month	4	7.0
Length of stay	≤1 year	1	1.8
	2–10 years	14	24.6
	11–20 years	10	17.5
	≥20 years	32	56.1

Table 5: Operational definitions of research variables

Variable	Definition	Measurement Items	Source
GB	The structure and use of building processes that are environmentally responsible and resource-efficient throughout the building's life cycle	11 items	Alwan *et al.*, 2015; Hwang and Tan, 2012
GI	Innovate in technology for energy saving, pollution prevention, waste recycling, and green product design	10 items	Khan *et al.*, 2021; Wang and Yang, 2020
GHRM	Implementation of human resource management policies and practices for sustainable resource utilization	6 items	Opatha and Arulrajah, 2014
GH	Hospitals that are designed, built, renovated, operated, and maintained by considering the principles of health and environmental sustainability	14 items	Azar *et al.*, 2015 Shaabani *et al.*, 2020
EFH	Hospitals that implement sustainable development, optimizing the use of natural resources and human resources by harmonizing human activities with the ability of natural resources to support them	17 items	Khan *et al.*, 2021 Li *et al.*, 2013

WPRPH is 57 family cards, which is very small because it is less than 100. Based on this condition, this study uses the entire population as a research sample, so the characteristics of the respondents for the community around WPRPH can be seen in Table 4.

Based on Table 4, it can be explained that the distribution of the number and percentage of respondents is for the community around WPRPH. First, women's society responds more to efforts to achieve EFH. Second, people aged 36–45 years respond more to efforts to achieve EFH. Third, people with senior high school education respond more to efforts to achieve EFH. Fourth, people who have an income of 100–235 USD/month respond more to efforts to achieve EFH. Fifth, people who have lived ≥20 years respond more to efforts to achieve EFH.

Research variable

The variables analyzed in this study consisted of exogenous variables (GB, GI, GHRM) and endogenous variables (GH and EFH), where indicators of each of these variables can be seen in Table 5.

This study also builds a research model to link variables in one unified research framework, which so far has been neglected. Then, each variable will contribute to other variables to create an EFH at WPRPH (Fig. 1).

The influence of GB on GH

The implementation of GB will be much faster and

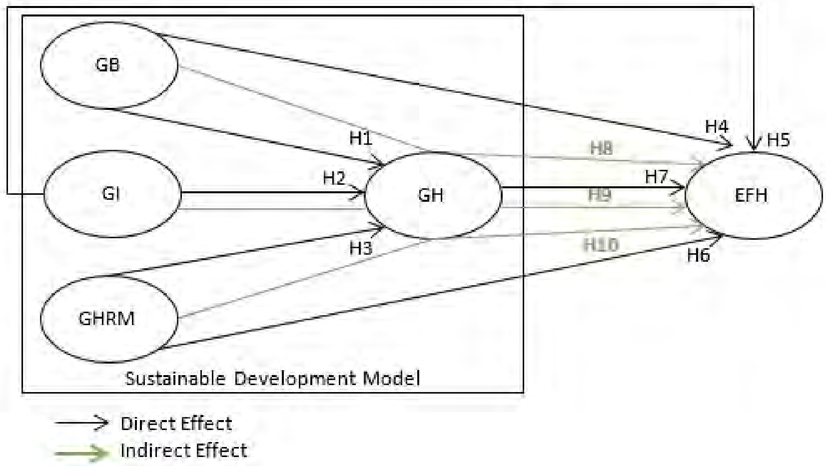

Fig. 1: Research variable linkages

have lower maintenance operational costs because the GB concept will be paired with solar panels to save electricity costs (AbdRahman *et al.,* 2021). Then, where it is seen that the increase in carbon accumulation will increase the number of inpatients in the hospital (Salvaraji *et al.,* 2023), the GB concept will also minimize reducing carbon footprint because it can reduce damage to the atmosphere and the earth's environment (Amran and Muhtazaruddin, 2018; Dhillon and Kaur, 2015). In addition, the use of GB will be more durable and longer because it is related to the use of quality construction materials (Zhan *et al.,* 2022).

H1: GB has a significant effect on GH

The influence of GI on GH

The GI aspect consists of management, process, product and technological innovation criteria (Issa and Jabbouri, 2022). Greater government efforts in this area will increase the incentives of companies to increase green proactivity. Governments that focus on increasing the availability of information regarding corporate environmental practices will intensify the positive effects of differentiation through GI (Aragón-Correa *et al.,* 2013).

H2: GI has a significant effect on GH

The influence of GHRM on GH

GHRM can be very effective in developing a green culture in an organization. So, to achieve GH, green practices must be identified and implemented (Gupta., 2018; Roberts *et al.,* 2016). GHRM increases employee commitment and leads to eco-friendly behavior by staff (Jackson *et al.,* 2014; Kim *et al.,* 2019).

H3: GHRM has a significant effect on GH

The influence of GB on EFH

The application of a project management framework for GB construction should be developed to overcome obstacles, such as promoting the adoption of sustainable construction in future projects (Al-Ghamdi and Bilec, 2017; Wood *et al.,* 2016). The construction of eco-friendly health infrastructure will use local and sustainable supplies of building materials to achieve EFH (Dhillon and Kaur, 2015).

H4: GB has a significant effect on EFH

The effect of GI on EFH

GI will drive process, product, and organizational improvements by increasing technological capabilities, but also by preventing pollution and saving energy, which will support the creation of EFH (Khan *et al.,* 2021).

H5: GI has a significant effect on EFH

The effect of GHRM on EFH

GHRM can be more useful if it is adopted by an organization as part of a broader sustainable development or green management philosophy rather than just a time bound small isolated step (Pinzone *et al.,* 2016). GHRM implementation can help organizations to improve company performance, especially environmental performance and achieve a green corporate culture (Khan and Zubair, 2019).

H6: GHRM has a significant effect on EFH

The effect of a GH on EFH

The implementation of GH is a hospital concept that is designed by empowering natural potential as the main resource so that it is friendly to the environment and saves energy expenditure (Renko *et al.,* 2018), where creating an environmental management system in the hospital requires serious and sustained action and coherent views from managers (Mohrman and Winby, 2018; Shaabani *et al.,* 2020).

H7: GH has a significant effect on EFH

The effect of GB on EFH mediated by GH

GB has an influence on EFH so that the basic structure level, the life cycle of construction materials assessed, such as concrete construction and steel construction, and meaning that steel structures in buildings are more environmentally friendly than reinforced concrete structures (Najjar *et al.,* 2022), shows that cement and steel have a higher impact than steel beams (Kumari and Kumar, 2020). Furthermore, its implementation must be supported by a design that empowers natural potential as the main resource (Kamath *et al.,* 2019).

H8: GB has a significant effect on EFH mediated by GH

The effect of GI on EFH mediated by GH

GI consists of green product innovation, recycling, and green publicity. Business sustainability also has three dimensions, namely financial performance, environmental performance, and social performance. The results of the study show that GI has a significant effect on business continuity in the future (Arfi *et al.,* 2017; Li *et al.,* 2020). GI can express a positive and significant impact on an organization's environmental performance through the implementation of environmentally friendly practices (Seman *et al.,* 2019).

H9: GI has a significant effect on EFH mediated by GH

The effect of GHRM on EFH mediated by GH

GHRM consists of cultural, organizational, and individual factors, which reinforce attitudes and environmental performance in hospitals. GHRM implementation with support from managers can provide a context for hospital environmental activities using environmentally friendly facilities (Rawashdeh, 2018), whereby, then, the necessary green structures will systematically accelerate the steps toward the goals of the hospital's green management (Paillé *et al.,* 2020). In addition, it also improves GH performance and staff motivation to participate in green activities (Seyedein and Mesbahi, 2020).

H10: GHRM has a significant effect on EFH mediated by GH

Data analysis technique

The analysis technique used in this study is the structural equation model or commonly called the Structural Equation Modeling (SEM)-Partial Least Square (PLS). SEM is a multivariate analysis technique that combines factor analysis and regression analysis with the aim of examining the relationship between variables in a model, both between indicators and their constructs and relationships between constructs. Where PLS is an alternative approach that shifts from a covariance-based SEM approach to a variance-based one, SEM makes it possible to see the relationship between variables simultaneously and take into account direct and indirect effects between variables.

RESULTS AND DISCUSSION

Outer loading

Outer loadings are tables containing loading factor (LF) to show the correlation between indicators and latent variables. The LF value must be greater than 0.7 then it is said to be valid. However, if the LF value is less than 0.7, then the indicator must be removed and the model must be recalculated. After evaluating the LF value, the next step is to evaluate the value of composite reliability (CR) to measure the actual reliability value of a variable with the provision that the value must be more than 0.6. Then, the next stage is to evaluate the average variance extracted (AVE) value, this describes the magnitude of the variance or diversity of manifest variables that can be owned by the latent construct, with the provision that the value must be more than 0.5. The last stage is evaluating the value of Cronbach alpha (CA), which measures the lower limit of the reliability value of a construct with the provision that the value must be more than 0.6. Based on this explanation, the results for LF, CR, AVE and CA can be seen in Table 6.

Table 6 informs about the outer loading results that have been carried out for this study. First, the LF results for all items for all variables are declared valid because the resulting values are greater than 0.7. Second, the

CR results for all variables show reliable values. Third, the AVE results for all variables are above the minimum criterion of 0.5, so that more than half of the diversity of the indicators. Fourth, CA results for variables are those with values above 0.6, which indicates a reliable value.

Discriminant validity

Discriminant validity (DV) is the degree to which a construct really differs from other constructs by empirical standards. This study uses the heterotrait-monotrait ratio (HTMT) approach to analyze DV. HTMT is the ratio of the correlation between traits with the correlation within the trait with the provision that the value must be less 0.85. This explanation; the results for DV using the HTMT ratio approach for this study can be seen in Table 7, where all HTMT ratio values are below the recommended value. So, within the same model the GB, GI, GHRM, GH, and EFH constructs differ from each other.

Then, Table 7 summarizes the results of testing the hypothesis of this study using a confidence level of α = 5% (0.05). This stage can be obtained after going through the process of analyzing the outer model and inner model, so that the results of the hypothesis testing arrive at the coefficients that correspond to each hypothesis. Based on the analysis that has been done, if the Probability (P) value is less than 0.05, then the hypothesis is proven to be accepted and vice versa. Parameters considered for the proposed sustainable development model are represented by GH, GB, GI and GHRM because all of these variables support each other so that EFH can be realized in WPRPH. The hypotheses in this study are divided into two categories, including H1 to H7 analyzing a direct relationship. Meanwhile, H8 to H10 analyze an indirect relationship because there is a mediating effect.

Table 7 informs that all the hypotheses put forward in this study are proven to be accepted because the p value for each hypothesis is less than 0.05. Furthermore, the direction coefficient for the hypothesis consisting of direct and indirect relationships in this study is positive for all hypotheses.

The effect of GB on GH at WPRPH

Implementation of GB will encourage the achievement of GH in WPRPH, where the contribution is 0.187 and has a significant effect on α 1 per cent (0.008).The use of environmentally friendly alternative materials such as mild steel for the roof framework at WPRPH. Furthermore, the use of environmentally friendly raw materials can save costs and reduce the impact on ecosystems on the environment, such as the use of alternative materials in the form of mild steel which will reduce costs and help maintain environmental ecosystems by avoiding the use of wood and destruction of the forest environment. Apart from that, the use of gypsum in room insulation will also reduce the risk of an earthquake due to the use of light and strong materials, so that the building life cycle according to the GH concept will be realized. Then, a new building at WPRPH has been designed by making piles buried underground as an earthquake-resistant foundation with a tested structure. Meanwhile, the old WPRPH building was demolished because it was not in accordance with the hospital development plan (master plan). However, for buildings that can still be utilized, renovations have been carried out to make them equivalent to new buildings, so as to create EFH. This will continue to be done until the next stage of development can be carried out. On the other hand, so as to encourage savings in electricity use, WPRPH also has good windows and glass, so that sunlight can enter employees' work rooms and inpatient rooms for patients. his condition is also supported by the availability of a good and comfortable waiting room, such as for outpatient care which has been neatly arranged and placed in one building with sufficient lighting and during the day can take advantage of sunlight in the room because the partition between the waiting room and the courtyard uses a very wide glass partition. This condition is in line with the results of research by Alwan *et al.* (2015), in which they argue that GB modeling will lead to cleaner production in the construction industry.

The influence of GI on GH at at WPRPH

Implementation of GI will encourage the achievement of GH in the WPRPH, where the contribution is 0.230 and has a significant effect on α per cent (0.003). Implementation of online registration services and conducting online consultations using social media such as WhatsApp, so that EFH services at WPRPH run effectively and efficiently. In addition, receiving input, suggestions, and complaints from patients, visitors and employees via the website and social media has gone well, in which all complaints submitted can be used as evaluations in the future and contribute to creating EFH.

Table 6: The assessment results of LF, CR, AVE, and CA

Indicator	LF	CR	AVE	CA
GB		0.952	0.659	0.948
The construction of the building uses raw materials with Indonesian national standards	0.741			
Building materials using environmentally friendly materials	0.876			
All 6xced have been used according to their function	0.770			
Waste installations are placed properly and neatly	0.816			
Clean 6xced installation 6xced well	0.823			
The generator building is placed in an 6xce that does not generate noise	0.823			
Doors and 6xcedes use aluminum	0.792			
Gypsum is used to insulate the room	0.812			
Mild 6xced is used for the roof frame as a substitute for Wood	0.838			
The building has an earthquake-resistant design	0.837			
The building makes use of doors, 6xcedes and ventilation to allow sunlight throughout the room	0.796			
GI		0.954	0.686	0.949
Accept patient registration with the online system	0.837			
Receive suggestions and complaints from the public through the WPRPH website and social media	0.871			
Using a hospital management information system application in providing service data	0.819			
Harnessing solar power for outdoor lighting	0.816			
Provide free wifi facilities for employees and visitors	0.817			
Perform online prescription delivery services to the designated pharmacy	0.822			
Using a temporary solid medical waste storage machine	0.859			
Using an WWTP machine to treat liquid medical waste	0.857			
Collaborating with the Environmental Service in realizing EFH	0.853			
Using an online system for ordering hospital products	0.724			
GHRM		0.939	0.762	0.938
Hospital employees sort medical and nonmedical waste before placing it in a landfill	0.850			
Hospital employees collaborate with visitors in preserving the environment	0.898			
Employees, visitors, and the community around the hospital reduce the use of plastic bags	0.867			
Refill 6xced is available for employees and visitors	0.861			
Hospital employees and visitors use 6xced only as needed	0.875			
Hospital employees and visitors prefer to use public transportation to the hospital	0.887			
GH		0.957	0.634	0.955
Hospital leaders establish pro-environmental policies	0.702			
The hospital manages chemicals well	0.846			
The hospital carries out waste management and the processed products are safe for disposal into public waste channels after being tested for the level of contamination	0.768			
The hospital conducts periodic checks of liquid waste in the health laboratory	0.822			
The hospital separates medical and nonmedical waste	0.807			
Hospitals pack solid medical waste according to its type	0.850			
The hospital carries out special packaging of radioactive waste	0.786			
The hospital periodically measures radiation levels	0.800			
The hospital uses a lighting system in the room by utilizing sunlight except at night	0.816			
Hospitals use alternative energy / substitute for electrical energy such as solar electricity	0.786			
The hospital periodically checks expired medicines and pharmaceutical materials	0.787			
Hospital use of medical equipment that does not cause noise	0.716			
The hospital uses operational vehicles that are fuel efficient	0.778			
The hospital conducts outreach to the community to 6xcede EFH	0.860			
EFH		0.956	0.579	0.954
There are plants as oxygen producers outside the building	0.710			
The air still feels fresh outside the building	0.774			
There is no noise when in a hospital environment	0.769			
The smell of sewage does not cause disturbance to visitors	0.704			
Cool and comfortable air in the room for patients and employees	0.791			
Adequate lighting throughout the room	0.768			
All 6xced are clean and trash free	0.730			
The local community can increase their income by trading or other businesses	0.803			
Hospitals absorb labor and reduce unemployment for local people	0.753			
The presence of WPRPH brought local investors to open businesses around the hospital	0.789			
The people of West Pasaman and its surroundings can easily reach health services	0.778			
Provide health insurance to employees	0.776			
The hospital is also an educational institution for employees and the community.	0.755			
The hospital is also a research facility for students and students	0.758			
Hospital employees carry out Friday sharing activities with the patient’s family	0.819			
Convey messages about environmental protection	0.730			
Minimizing the use of engines that produce emissions	0.719			

Table 7: DV test results (HTMT ratio)

Variable	GB	GH	GHRM	GI
GB				
GH	0.461			
GHRM	0.571	0.475		
GI	0.591	0.469	0.535	
EFH	0.608	0.559	0.575	0.568

Then, innovations to technology at WPRPH such as online prescription delivery services to hospital pharmacies or other pharmacies have been running on an ongoing basis, so as to make it easier for patients to obtain drugs. This is also evidenced by the implementation of an online system for ordering products for hospital needs, so that it can reduce the cost of obtaining products and minimizing the use of time to obtain products. On the other hand, while, according to Aguilera-Caracuel (2013), GI incorporates technological improvements that save energy, are environmentally friendly or enable waste recycling for corporate environmental management, which contributes to business sustainability, WPRPH has also improved its services to visitors in managing waste through temporary solid medical waste storage machines so as not to have an impact on the hospital environment and the surrounding environment.

The influence of GHRM on GH at WPRPH

Implementation of GHRM will encourage the achievement of GH in WPRPH, where the contribution is 0.235 and has a significant effect on α 1 per cent (0.000). WPRPH employees sort medical and nonmedical waste before placing it in a landfill. Then, WPRPH employees collaborate with visitors and the community around WPRPH in preserving the environment in a program that is a form of creating EFH owing to the reason that, by increasing the competence of employees, visitors, and the surrounding community, it is easier to build EFH. The results of this study are also supported by the findings of Opatha and Arulrajah (2014), in which the aim of GHRM is to create, improve, and maintain greenery for every employee so as to provide maximum contribution to the role of preservation, conservation, nonpolluting or nonpolluting sources. Meanwhile, Yong *et al.* (2020), in their study argue that the implementation of GHRM is a resource, and that economic development or human activity in the workplace will not have a negative impact on the environmental ecosystem.

The influence of GB on EFH at WPRPH

Implementation of GB will encourage the achievement of EFH in WPRPH, where the contribution is 0.263 and has a significant effect on α 1 per cent (0.000). GB has had a good impact on sustainable development as WPRPH has done by using aluminum as a substitute for wood for frames, doors and windows. This action has a positive impact on the hospital environment such as the lack of use of wood and results in a reduction in the use of materials derived from nature. The results of this study are in line with several relevant studies, including Hwang and Tan (2012), who found that GB was built based on sustainable construction principles, which took into account ecological, social, and economic issues. Meanwhile, according to Dhillon and Kaur (2015) unsustainable and inefficient buildings, unsafe disposal of hospital waste and untreated waste create an unhealthy environment. Furthermore, the GB rating system measures a building's sustainability by applying a series of criteria organized into various categories, such as site selection, energy, water, resources, materials, and environment (Nilashi *et al.* 2015).

The influence of GI on EFH at WPRPH

Implementation of GI will encourage the achievement of EFH in WPRPH, where the contribution is 0.192 and has a significant effect on α 1 per cent (0.014). GI at WPRPH is good and has implemented services in the form of online registration, providing information through the application system, thereby reducing the use of paper, reducing expenses for patients to meet in person and reducing the use of fuel oil which results in reduced sources of emissions from vehicles. Then, medical waste management has also been carried out using innovative equipment to create EFH in the form of providing medical waste processing machines, so that the waste can be reused or recycled. The results of this study are in line with several relevant studies, including sustainable development units, which are sustainable health care as something that provides high-quality environmental maintenance and improves public health without causing severe ecological damage (Khan *et al.,* 2021). Buildings without energy and related design techniques and technologies will be cost efficient in life cycle and impact on environment, climate change and social policy issues (Li *et al.,* 2013).

The influence of GHRM on EFH at WPRPH

Implementation of GHRM will encourage the achievement of EFH in WPRPH, where the contribution is 0.197 and has a significant effect on α 1 per cent (0.003). GHRM on WPRPH is quite high in receiving environmentally friendly information. The concern of employees, visitors, and the surrounding community for the environment can be seen from their attitude and behavior in handling waste, in which they want and care to sort waste according to its type. In addition, employees and visitors have also used water as needed (Le Dinh *et al.* 2022; Brotosusilo *et al.* 2022; Sivakumar *et al.* 2022; Ghazali *et al.* 2021). The results of this study are also supported by several relevant studies, including Masri and Jaaron (2017), in which they found that GHRM is used to promote the use of sustainable resources for environmental sustainability. According to Khan and Zubair (2019), it is stated that steps that can be taken by organizations to support an environmentally friendly mission need to adopt sustainable and GHRM management practices.

The influence of GH on EFH at WPRPH

Implementation of GH will encourage the achievement of EFH in WPRPH, where the contribution is 0.241 and has a significant effect on α 1 per cent (0.000). Respondents rated the WPRPH leader's pro-environmental policy as quite good, so with this it is necessary to maintain and even increase environmentally friendly behavior in order to create EFH. Then, the management of chemicals that has been carried out is very good, so that it can help encourage sustainable development that is carried out. This is evidenced by providing a place to store chemicals that can have a negative impact on the hospital environment and the surrounding community. Furthermore, the management of waste and its processed products is considered quite well because testing for the level of pollution is carried out routinely. In addition, the segregation of medical and nonmedical waste has been carried out well, so that medical waste can be collected according to its type. In addition, the use of direct sunlight is very good which is supported by most of the glass building materials, thereby minimizing spending on electricity costs. In general, for the building and the availability of facilities in an effort to create EFH in WPRPH, the respondents considered it good because it has rooms with clean conditions starting from inpatient rooms, toilets, prayer rooms, and waiting rooms. This makes employees, visitors, and the surrounding community feel comfortable. The results of this study are also supported by several relevant studies, including environmentally sound development toward sustainability which can involve economic, social, and environmental aspects of human and organizational activities at the local, national and international levels Renko (2018). GH is to eliminate the role of the hospital in the weight of the waste burden (Setyowati *et al.,* 2013). The same thing was conveyed by Shaabani *et al.* (2020) that GH is one that supports public health by reducing environmental risks.

The influence of GB on EFH mediated by the GH at the WPRPH

GH mediates GB in increasing EFH in WPRPH, where the contribution is 0.045 and has a significant effect on α 1 per cent (0.036). GH certainly already has environmentally friendly buildings such as using national standard building materials and using alternative building materials that do not pose a risk to the building itself or to the employees, visitors, and the surrounding community (Opatha and Arulrajah, 2014). Alternative building materials can certainly streamline hospital expenses because they have affordable prices and are durable. After the creation of GH which is supported by GB, hospital management can be more flexible in carrying out environmentally friendly sustainable development which can have a positive impact on all parties involved in it. The benefit for employees and visitors to the hospital is that all activities around the hospital can run well because the risks that arise have been minimized from environmentally friendly buildings. This being the case while the benefits for the surrounding community can increase their standard of living by carrying out an activity that has high value and is useful for others which can ultimately improve the economic, social, environmental, and maintenance and rehabilitation of the environment.

The influence of GI on EFH mediated by GH at WPRPH

GH mediates GI in increasing EFH in WPRPH, where the contribution is 0.055 and has a significant effect on α 1 per cent (0.022). GH was created from geographic information system (GIS) that have been implemented by hospital management, including using technological developments effectively so that hospitals can implement an online patient registration system and accept complaints or suggestions given by visitors via the information web provided by Shaabani *et al.* (2020). Then, GH is also a supporter in the implementation of sustainable development in the present and the future effectively because the hospital is based on an EFH. Ajbar *et al.* (2023) revealed that it is necessary to innovate waste treatment in hospitals because medical waste can endanger health workers and patients. Furthermore, a good GI can facilitate all aspects related to health services because the easier it is to get services, the more satisfied visitors are with the services provided. So with that, GH is able to mediate GIS in increasing EFH, so that the goals set by hospital management are to provide the best service for employees, visitors, and the surrounding community.

The influence of GHRM on EFH mediated by GH at the WPRPH

GH mediates GHRM in increasing EFH in WPRPH, where the contribution is 0.057 and has a significant effect on α 1 per cent (0.015). With the most important GHRM practices being identified and prioritized, measured by several criteria, such as the willingness of employees to sort waste and place it according to its type, in order to assist hospital leaders in creating better hospital development, it is necessary to have contributions from GH and GHRM in the sense of having competence, behavior, and attitudes that are in favor of hospital development. In addition, employees are also able to collaborate with visitors and the surrounding community to preserve the environment and what is very important is that employees are able to use hospital support facilities effectively and efficiently in order to minimize hospital operating costs (Khan and Zubair, 2019). So with that, GHRM can determine the sustainable development of hospitals that are supported by GH.

CONCLUSION

The conclusion of this study consists of three important points. First, GB, GI, and GHRM have a positive and significant effect on GH and EFH in WPRPH. Second, GH has a positive and significant effect on EFH at WPRPH. Third, GH mediates GB, GI, and GHRM in increasing EFH at WPRPH. This study finds a novelty as an important finding, in which the sustainable development model consisting of GH, GB, GI, and GHRM is a driving factor in achieving the context of EFH in WPRPH. In addition, the role of GH needs to be increased to strengthen the influence of GB, GI, and GHRM on EFH in WPRPH. The recommended modeling application from the results of this study is the application of EFH which is able to contribute to environmentally sound development because WPRPH has packaged solid medical waste according to its type, provided a special room for chemical storage, carried out routine and periodic checks on the chemical and bacteriological content of its liquid waste. The attention of management is needed to determine pro-environmental policy directions, for example by making regulations in the form of director's regulations related to hospital environmental management, in addition to the following rules and sanctions for violations of the rules set by the director's regulations regarding hospital environmental sustainability. The policies that can be implemented to achieve this include there being the necessity in the implementation of GB to make EFH work properly by implementing environmentally friendly indicators, especially those related to GB, both those related to GB material quality, the use of modeling building information to reduce construction dematerialization and the use of substitution and material specifications as well as the use of designs for the building life cycle, which needs to be applied when the development process is underway. Innovative approaches to achieving sustainable infrastructure and design games in creating EFH include reusing all used materials that can still be used and still meet the requirements in order to reduce the amount of construction waste and minimize the carbon footprint, using wood materials that are legally certified according to Government Regulations of wood origin and legally free from illegal timber trade and rooms with high occupant density equipped with installation of carbon dioxide gas sensors in the room of no more than 1,000 ppm. Then, in the implementation of GI it is necessary to maximize the existing cold storage as medical waste storage because if it is not maximized its use will cause problems, such as aesthetics, physical, and psychological health for all employees, visitors, and the community around WPRPH. Furthermore, if medical waste exceeds the capacity of the existing cold storage, the hospital should budget for additional purchases of cold storage, so that medical waste can be accommodated properly. On the other hand, GI can be integrated into hospital settings to improve environmental performance including energy efficiency and conservation, in which hospital buildings are equipped with electricity meters for each electricity load sub-system separately, especially between hospital and medical service facilities, perform electricity calculations, measure energy efficiency, use natural lighting, equipped with ventilation, calculate local climate change impacts through measuring CO_2 emissions and using new and renewable energy sources. While in the implementation of GHRM it is necessary to increase knowledge of medical waste management in order to better understand how to manage medical and nonmedical waste and the importance of outreach to all employees in carrying out medical waste management so that waste managers and producers work together to maximize waste management in WPRPH, another innovation is water conservation, in which the hospital building is equipped with a water meter, reducing water use, using water-efficient water fixtures, installing waste water recycling installations, using alternative water sources, making efforts to absorb rainwater and water efficiency for watering gardens. In addition, in the implementation of GH it is necessary to carry out continuous supervision between GB, GI and GHRM because this is an integral component so that EFH in WPRPH can be realized to encourage sustainable development through controlling environmental, economic, social, and climate change. Governments and policy makers support the adoption of EFH through incentives, such as holding a GH contest to promote hospitals that have a more environmentally perspective in hospital management, especially in terms of waste management, environmentally friendly materials, efficient use of resources, and other innovations. Then, it can also go through regulations such as policies: these being, first, promoting the commitment of hospital managers to implement GH principles; Second, striving to protect health, safety, and create comfort for hospital residents by controlling negative environmental impacts resulting from hospital activities; Third, implementing the principle of efficient use of energy, water, and material resources. Although this study makes a number of important contributions to the study of WPRPH, it still has some limitations: First, this study uses a proportionate cluster random sampling technique as a sample, so that it becomes a limitation in sampling because it consists of three criteria, namely employees, visitors, and the community. For further research, it is expected to use accidental sampling as a sampling technique so that the sampling is done in one direction only and the results are more specific; Second, the object of research is only carried out in one hospital, so there are no other hospitals as a comparison, so future researchers need to add research objects that are engaged in the same field, so that the insights obtained from research are broader; Third, this study only relied on the data collection process using a questionnaire, so future researchers need to combine questionnaires and interviews as a data collection technique.

AUTHOR CONTRIBUTIONS

F. Aini, the corresponding xced, has contributed in prepared all the tables and figure and interpretation of the results, participated in the interpretation of the SEM-PLS results and manuscript preparation. A. Irianto, has contributed in supervising the first xced in prepared all the tables and figure and interpretation of the results, participated in the interpretation of the SEM-PLS results and manuscript preparation. S. Amar, has contributed in supervising the first xced in prepared all the tables and figure and interpretation of the results, participated in the interpretation of the SEM-PLS results and manuscript preparation.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication, and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
α	Alpha
=	Similarity
()	Parenthesis
+	Plus
AVE	Average variance extracted
CA	Cronbach Alpha
CR	Composite reliability
DV	Discriminant validity
E	Error
et al.	Et Alia
Eq.	Equation
EFH	Environmentally friendly hospital
GB	Green building
GIS	Geographic information system
Fig.	Figure
GH	Green hospital
GHRM	Green human resource management
GI	Green Innovation
H	Hypothesis
H1	Hypothesis 1
H2	Hypothesis 2
H3	Hypothesis 3
H4	Hypothesis 4
H5	Hypothesis 5
H6	Hypothesis 6
H7	Hypothesis 7
H8	Hypothesis 8
H9	Hypothesis 9
H10	Hypothesis 10
HTMT	Heterotrait-Monotrait
LF	Loading Factor
n	Sample Size
N	Population Size
P	Probability
PLS	Partial Least Square
P-value	Probability of obtaining results
SEM	Structural equation modeling
USD	United States Dollar
WPRPH	West Pasaman Regional Public Hospital

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SPECIAL ISSUE: Eco-friendly sustainable management
CASE STUDY

Carbon dioxide net assimilation exchange in a young pecan nut orchard during the growth cycle

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ABSTRACT

BACKGROUND AND OBJECTIVES: Pecan nut trees (Carya illinoensis K), due to their condition as woody and long-living species, in addition to the contribution of nuts for consumption, may also have an essential role in assimilating carbon dioxide and sequestering atmospheric carbon. This study aimed to determine the carbon dioxide net ecosystem exchange of an orchard of young pecan nut trees in northern Mexico, and its relationship with the growth months of the trees.

METHODS: The study was carried out from March to November 2017 in a six-year-old pecan nut tree orchard containing trees of the Western Schley and Wichita varieties. The orchard is drip-irrigated with buried tape. The carbon dioxide net ecosystem exchange between the canopy of the orchard trees and the atmosphere was determined with eddy covariance measurements using a three-dimensional sonic anemometer and an open-path infrared carbon dioxide analyzer.

FINDINGS: The highest daytime carbon dioxide net ecosystem exchange rate corresponded with the peak absorption rate of photosynthetically active radiation absorbed by the trees' canopy. It was observed between 11:00 and 14:00 hours throughout the growth months of the trees. The highest carbon dioxide net ecosystem exchange rate was observed in June, at 7 micro mol square meter per second. The relationship between the carbon dioxide net ecosystem exchange and the photosynthetically active radiation absorbed by the trees' canopy through the growth months was described using a rectangular hyperbolic function. From March to September, the carbon sequestration of the young pecan nuts was 0.962 tons of carbon per hectare.

CONCLUSION: The highest carbon dioxide diurnal assimilation rate was observed in May, at 5 717.95 millimoles per square meter. Despite the young age of the pecan trees, the orchard has a retention capacity of 0.962 tons of carbon per hectare for the months evaluated. The young pecan orchard significantly contributes to the assimilation and retention of atmospheric carbon that will increase with the growth of the trees, due to greater leaf and biomass development.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
44	3	3

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INTRODUCTION

Carbon dioxide (CO_2) is a greenhouse gas, generated by burning fossil fuels, that induces global warming and climate change (Gizer *et al.,* 2022; Rehman *et al.,* 2022; Prasara-A and Bridhikitti, 2022). Plant ecosystems also absorb this gas (photosynthesis process) for their growth and development (Pimienta, 2007; Garsetiasih *et al.,* 2022; Hidayah *et al.,* 2022). The study of the dynamics of CO_2 flux between plant ecosystems and the atmosphere is important due to its relationship with global warming. The contribution of vegetation to the global carbon cycle is fundamental due to atmospheric carbon sequestration in plants' biomass (Eftekhari, 2022; Sahoo *et al.,* 2022; Dhayalan and Karuppasamy, 2021). Previous studies on the CO_2 assimilation rate and atmospheric carbon sequestration have been carried out in various natural plant ecosystems. For example, the study of Bernal *et al.* (2018) reported the CO_2 assimilation rate, in tons of CO_2 per hectare per year (t/CO_2/ha/y), of a conifer forest in a boreal climate, and of Eucalyptus (*Eucalyptus globulus*) in a tropical humid zone. The rate of carbon sequestration (t/C/ha/y) of inland wetlands, peatlands, and coastal wetlands was reported by Li *et al.* (2023). In another study, in a forest of the species *Gmelina arborea*, *Eucalyptus tereticornis*, *Cassia siamea*, and *Leucaena leucocephala*, carbon sequestration potential was evaluated (Kaith *et al.*, 2023). However, there is not much information on the participation of agricultural systems in this context (Rojas-García *et al.,* 2015; Sharman *et al.,* 2021). Due to their condition as woody and long-living plant species, pecan nut (*Carya illinoensis K.*) trees, in addition to their use for walnut production, may play an essential role in CO_2 assimilation and atmospheric carbon sequestration. The average biomass accumulation in a mature pecan orchard can reach up to 22 tons per hectare (t/ha) (Wang *et al.,* 2007; Dold *et al.,* 2019). In Mexico, pecan walnut cultivation began in the state of Chihuahua 400 years (y) ago, and the establishment of orchards for commercial purposes dates back to 1946; therein, currently, there are trees up to 71 y old (Ojeda-Barrios *et al.,* 2009; Concilco-Alberto *et al.,* 2022). Most of the studies carried out recently on pecan nut trees have been oriented mainly to the agronomic management of the crop, such as pruning, phytosanitary control, fertilization, trees' water requirements, and irrigation scheduling (Samani *et al.,* 2011; Zermeño-González *et al.,* 2014). For example, Andales *et al.* (2006) studied effective pruning management using a growth simulation model. Bock *et al.* (2012) evaluated the effect of a fungicide on controlling walnut scabs. Ojeda-Barrios *et al.* (2014) performed foliar fertilization with Zinc to improve yield in an eight-year-old pecan nut orchard. Samani *et al.* (2011) and Zermeño-Gonzalez *et al.* (2014) used the eddy covariance method to measure water vapor and CO_2 fluxes between the canopy of a pecan nut orchard and the atmosphere. Mexico is the leading exporter of shelled pecan nuts to the United States (Retes *et al.,* 2021), so its planted surface has increased significantly recently. In 2021, a total plant cover of 146,239.11 hectares (ha) of pecan nut orchards was reported, wherein the states of Chihuahua, Coahuila, Sonora, Durango, and Nuevo León accounted for 60.9, 14.9, 13.34, 5.2 and 2.9 percent (%) of total production, respectively (SIAP, 2021). The global increase in pecan orchards' establishment may contribute to CO_2 assimilation and atmospheric carbon storage. Under the hypothesis that young pecan nut trees may contribute to atmospheric carbon sequestration, the objective of this study was to determine the CO_2 net ecosystem exchange of an orchard of young pecan nut trees throughout the growth months in northern Mexico during the growing cycle of the year 2017.

MATERIALS AND METHODS

Study site

The study was carried out from March to November 2017 in a six-year-old pecan walnut (*Carya illinoensis* K.) orchard located in the General Cepeda Municipality, Coahuila State, Mexico (25° 28' 22.46" North (N), 101° 26' 40.06" West (W), at 1304 meters (m) above sea level (masl). According to the Modified Köppen Classification for Mexico, General Cepeda has a climate of the type BS0h'(h)x'(w)(e') (Copers, 2020), which is an arid, semi-warm climate. The average yearly temperature and average rainfall are 18.3 degrees Celsius (°C) and 265 mm, respectively. The pecan nut trees are planted in a rectangular planting framework, aligned in the north–south direction, with a spacing of 8 m between trees and 12 m between rows, covering an area of 11.6 ha. The varieties planted are Western Schley and Wichita. The orchard is drip-irrigated (with tapes buried 20 cm deep), the hoses are 1 m apart from each side of the trunk of the trees, and there are 16 emitters per tree (8 on each side) spaced 60 cm apart with a flow rate of 1.68 liters per hour (LPH). Two 12-hour irrigations are applied every six days.

Measurements and sensors

The CO_2 flux between the orchard canopy and the atmosphere was obtained with eddy covariance measurements using Eq. 1 (Zermeño-Gonzalez *et al.,* 2021):

$$FCO_2 = w^*P_{CO2} \quad (1)$$

where w is the vertical wind speed and ρco_2 is the density of CO_2. Variables with a prime symbol are the deviations from the mean, and the horizontal bar corresponds to the covariance between the variables for a specific time segment (30 min). The vertical wind speed (w) was determined with a three-dimensional sonic anemometer (CSI-CSAT3, Campbell Scientific, Inc., Logan, Utah, USA). The density of CO_2 in the air was measured with an open-path infrared analyzer (Open Path CO_2/H_2O analyzer, LI-7500. LI-COR, Lincoln, Nebraska, USA). Both sensors were placed at the center of the southern end of the orchard, 2 m above the trees' canopy, and connected to a CR1000 datalogger (Campbell Scientific, Inc., Logan, Utah, USA) to record the data. The three-dimensional sonic anemometer was oriented north so that the wind had at least 300 m of contact with the surface in the north–south direction, and 125 m in the east–west direction, before contact with the sensors. The operating frequency of the sensors was 10 Hz, and the covariances were generated at intervals of 30 min. The climatic conditions vary daily; however, the eddy covariance measurements also register the daily changes in weather data. The CO_2 net ecosystem exchange (NEE) (µmol/CO_2/m/s) between the orchard canopy and the atmosphere was obtained using Eq. 2 (Martens *et al.,* 2004):

$$\text{NEE} = \text{FC0}_2 + \frac{\Delta\rho CO_2}{\Delta t}\Delta z \quad (2)$$

where FCO_2 is the flux of CO_2 measured with the eddy covariance method (Equation 1) (negative sign towards the surface), and $\Delta\rho CO_2$ is the change of CO_2 density in a particular time segment Δt (30 min). Δz is the height above the ground surface at which flow measurements are made (5 m). The daily balance of the CO_2 NEE through the growth stages of the trees was obtained using the difference between the daytime (assimilation) and night-time (release) integrated values. The rate of photosynthetically active radiation (PAR) absorbed by the trees' canopy was obtained by placing two quantum sensors (model SQ-512, Apogge Inst., Logan, Utah, USA) 2 m above the tree canopy, one oriented toward the midpoint of a tree canopy (reflected PAR) and the other toward the zenith (incident PAR). The PAR absorbed by the trees' canopy was the difference between the incident and reflected PAR. Measurements were made at a frequency of 1 Hz (with the sensors connected to another CR1000 datalogger), and 30-min averages were obtained. The eddy covariance system measures the exchange of CO_2 fluxes from the atmosphere to the soil and the pecan trees. The CO_2 from and towards the ground depends on the soil properties (organic matter and water content, microorganisms, among others). Using the eddy covariance measurements, the CO_2 flux from the soil is considered. Fig. 1 shows an image of the orchard and the sensors used to take the corresponding measurements.

Relationship between the CO_2 NEE and the PAR absorbed by the trees' canopy

To assess the relationship between the CO_2 NEE and the PAR absorbed by the trees' canopy, we used a rectangular hyperbolic function, as shown in Eq. 3 (Stoy *et al.,* 2006; Moffat *et al.,* 2007):

$$\text{NEE} = \frac{\text{b1*PAR}}{\text{b2} + \text{PAR}} + \text{b3} \quad (3)$$

where b1 represents the highest photosynthetic capacity of the ecosystem (µmol/m²/s), b2 corresponds to the PAR value for the mean value of the photosynthesis rate (µmol/m²/s), and b3 symbolizes the daytime respiration rate of the ecosystem (µmol/m²/s). These parameters were obtained using nonlinear regression procedures (i.e., evaluations of functions using the Jacobian method).

Quantum yield and quantum efficiency of the orchard trees

The quantum yield (µmol CO_2/mmol photons) of

Fig. 1: Pecan nuts of 7-year-old trees and the sensors for eddy covariance measurements of the CO_2 net ecosystem exchange (NEE) and photosynthetically active radiation (PAR) above the trees' canopy

the orchard trees throughout the months of growth was obtained by dividing the moles of CO_2 assimilated during the daytime (NEE) by the mmol of photons absorbed at the same time (PAR). The quantum efficiency (%) was found using the relationship between the energy required (MJ) for the assimilation of the CO_2 moles and the energy content (MJ) in the PAR absorbed by the trees' canopy.

Statistical analysis

The differences in the trees' quantum yield and quantum efficiency during the growth months were evaluated using a completely randomized design. Each month was considered one treatment (using a total of seven months), and the repetitions were the number of days with information from each month. A Tukey's test (α ≤ 0.05) was used to compare the treatment means.

RESULTS AND DISCUSSION

CO_2 NEE and absorbed PAR

As the leaf area grows, the CO_2 assimilation rate increases, and the opposite occurs when the leaf area is reduced. At the beginning of the vegetative stage (March), the leaves of the trees were beginning their development, and the CO_2 net ecosystem exchange rate (NEE) (30 min averages) of the orchard trees was minimal compared to that observed in the following months (Fig. 2). During this stage, the CO_2 net ecosystem assimilation rate (the negative sign of NEE in Fig. 1) was, on average, less than -1.25 μmol/m^2/s; of approximately the same magnitude was the highest CO_2 net ecosystem release rate (the positive sign of NEE in Fig. 2) (night-time respiration), and this represents an approximate balance between the rate of assimilation and the release of CO_2 of the ecosystem. The highest daytime CO_2 NEE assimilation rate corresponded to the peak rate of photosynthetically active radiation (PAR) absorbed by the trees' canopy. This was observed between 11:00 and 14:00 throughout the growth months of the trees (Fig. 2). Due to the limited development of the trees' canopy during March, the absorbed PAR rate was lower (1 700 μmol/m^2/s) than that observed in the following months (Fig. 2). In June, when the trees already had full leaf development and the uppermost photosynthetic activity, the maximum daylight hours' CO_2 assimilation rate was up to -7 μmol/m^2/s, while the (night-time) release rate was only 2 μmol/m^2/s (Fig. 2). The rate of assimilation being greater than the rate of release is due to the formation

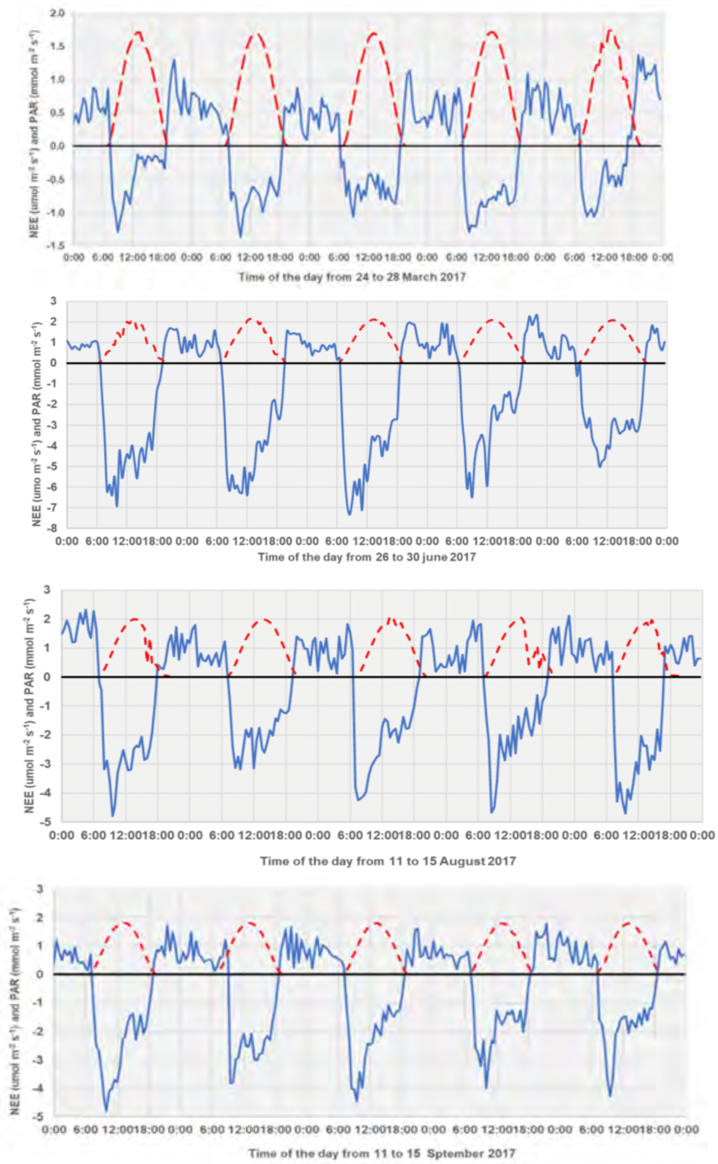

Fig. 2: CO_2 net ecosystem exchange rate (30 min average) (NEE) (the solid blue line), and photosynthetically active radiation absorbed by the tree canopy (PAR) (dashed red line), from an orchard of 7-year-old pecan trees at different times in their growth cycle.

of carbon compounds that can be used for wood growth and fruit development. In this regard, Wang *et al.* (2007) and Negi *et al.* (2003) mention that of the total assimilated CO_2, 46.4 % is allocated to the growth and formation of wood and fruits. The rate of PAR absorbed by the trees' canopy was up to 2 100 µmol/m^2/s. In August, the highest CO_2 daytime assimilation rate decreased to slightly lower values (-5 µmol/m^2/s), while the greatest CO_2 night-time release rate was up to 2 µmol/m^2/s, with the highest rate of PAR (up to 2000 µmol/m^2/s) being absorbed (Fig. 2). During September, the rate of the highest CO_2 assimilation was also -5 µmol/m^2/s, but the rate of the highest CO_2 release was less than 2 µmol/m^2/s, and the rate of maximum PAR absorbed was slightly less than 2 000 µmol/m^2/s (Fig. 2). Similar patterns have been observed in other crops.

For example, in a Kiwi (*Actinidia deliciosa*) orchard, the CO_2 assimilation peaked during May and June (up to -14 µmol/m^2/s) and decreased to -12 and -10 µmol/m^2/s in July and August, respectively (Rossi *et al.,* 2007). In a mature avocado (*Persea americana* Miller) orchard, the peak net assimilation rate was observed in April (-18.3 µmol/m^2/s), and decreased to a constant value (-10 µmol/m^2/s) in October (Nafees *et al.,* 2019). The CO_2 net ecosystem exchange values observed in this study are small, as the orchard was made up of young trees (of 7 years old) that had an average crown diameter of 4.78 m, which is equivalent to an area of only 15.75 m^2. This crown surface only covered 16.4 % of the total soil surface in a planting framework that had 12 m between lines and 8 m between trees. Most previous studies have been carried out in orchards of older pecan trees with a greater leaf area and biomass, and higher CO_2 assimilation rates. The CO_2 assimilation rate depends more on the trees' leaf area than the cultivar. In a pecan orchard of 35 y old trees wherein the canopy covers the whole soil surface, the CO_2 assimilation rate can be up to -17 µmol/m^2/s (Zermeño-Gonzalez *et al.,* 2014). The CO_2 NEE of three pecan nut genotypes (A1, A3, and A9) under pot growth conditions was -26.3, -25.6, and -27.5 µmol/m^2/s, respectively (Momayyezi *et al.,* 2022). In 25-year-old pecan nut trees of the cultivars Pawnee and Stuart, the CO_2 NEE rate was -11 and -9 µmol/m^2/s, respectively, for a PAR assimilation rate of approximately 700 µmol/m^2/s. (Lombardini *et al.,* 2009). For the Franquette cultivar (12-year-old trees), the CO_2 NEE was up to -16.9 µmol/m^2/s (Christopoulos *et al.,* 2021). Although weather conditions change during the hours of the day, from day to day, and from month to month, the results of this study showed that at the time of the highest incidence of solar radiation, the photosynthetically active radiation absorbed by the trees' canopy and the CO_2 net ecosystem exchange also have the highest values, and this applies from year to year.

Relationship between CO_2 NEE and PAR

The energy required for CO_2 assimilation is provided by solar radiation within the wavelength of 400 to 700 nanometers (nm). The relationship between CO_2 net ecosystem exchange (NEE) and the photosynthetically active radiation (PAR) absorbed by the trees' canopy (average of 30 min) through the growth months was described with a rectangular hyperbolic function (Fig. 3). This function depicts an increase in NEE (a bigger negative value) as the absorbed PAR increases. The NEE capacity of the canopy trees depends on the stage of growth. The trees had little foliar development in March and a low CO_2 absorption rate. For a PAR absorption rate of 1000 µmol/m^2/s, the NEE rate was -1.0 µmol/m^2/s. In May, the NEE increased to – 4.5 µmol/m^2/s for the same PAR absorption rate. In July, the same rate was 4.0 µmol/m^2/s, and in September, it decreased to -2.9 µmol/m^2/s (Fig. 2). Similar relationships have been observed in other plant ecosystems. In a plum (*Spondias purpurea* L.) orchard, the peak photosynthesis rate was up to -10.7 µmol/m^2/s on the days of the highest incidence of PAR (Ramirez and Pimienta, 2003). For four-year-old rubber plants (*Hevea brasiliensis Müll. Arg*.), the NEE reached a saturation of -25 µmol/m^2/s at an incident PAR of 700 µmol/m^2/s (Chayawat *et al.,* 2019). The coefficients b1 and b3 of the rectangular hyperbolic equation are indicators of the highest photosynthetic capacity and the daytime respiration rate of the orchard, respectively (µmol/m^2/s). Table 1 shows that in March, due to limited development of the trees' leaves, there was the lowest photosynthetic capacity of the orchard (lower value of b1). The highest value was observed in April, because the trees already had complete leaf development, with sunny days (slight cloudiness) and moderate temperatures. From May to July, the peak photosynthetic capacity of the orchard was very similar, and decreased in August and September. The daytime respiration rate (parameter b3 of the rectangular hyperbolic equation) (Table 1) was lower and approximately the same during March, April, and May. The peak rate of daytime respiration was observed in September (Table 1), probably due to the onset of leaf senescence. At this stage, new leaves are no longer produced, and the photosynthetic capacity of the leaves is reduced. Previous studies in controlled environments with Sunflower (*Helianthus annuus*), Lily (*Lilium candidum*), Maize (*Zea mays*), and Alfalfa (*Medicago sativa*) plants have also shown that the relationship between the net photosynthesis rate and the PAR rate can be described using a rectangular hyperbolic function (Sun and Wang, 2018). The relationship between NEE and PAR in young rubber trees (Hevea brasiliensis Müll. Arg.) was described using a rectangular hyperbolic function. The NEE was up to -4.94 µmol/m^2/s (Chayawat *et al.,* 2019). Studies conducted by Zhang *et al.* (2015) in a maize crop observed a direct proportional relationship between the PAR rate and the NEE rate.

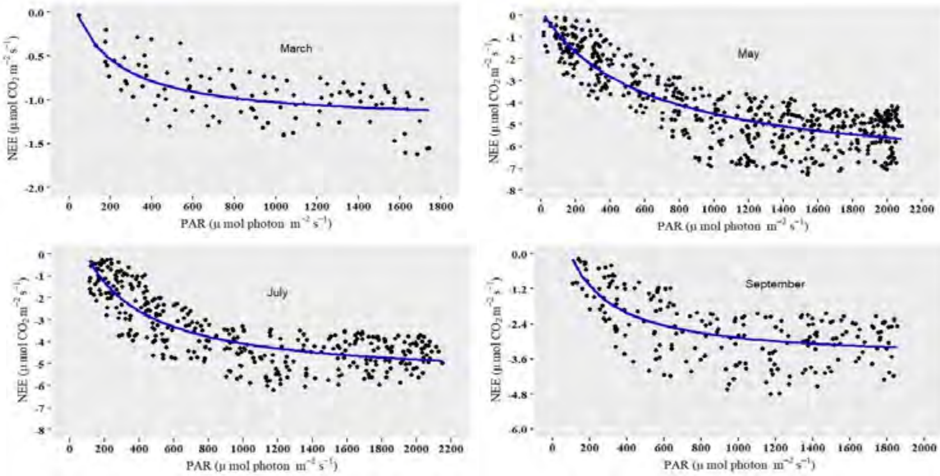

Fig. 3: Relationship between CO_2 net ecosystem exchange (NEE) and the photosynthetically active radiation (PAR) absorbed by the tree canopy of a seven-year-old pecan nut orchard in northern Mexico. The points represent the observed data, and the line corresponds to the adjusted NEE values with a rectangular hyperbolic function.

Table 1: Parameters of the rectangular hyperbolic function and coefficient of determination (r^2) in the growth months of a seven-year-old pecan nut orchard from northern Mexico.

Month	b1 (µmol CO_2/m^2/s)	b2 (µmol photons/m^2/s)	b3 (µmol CO_2/m^2/s)	r^2
March	-1.504	188.748	0.238	0.425
April	-8.58	942.610	0.223	0.805
May	-7.558	602.669	0.204	0.733
Jun	-7.258	246.215	1.306	0.512
July	-7.633	282.216	1.876	0.693
August	-5.350	204.500	1.387	0.339
September	-5.963	153.847	2.295	0.426

Quantum yield and quantum efficiency of orchard trees

Of the months evaluated, the quantum yield (expressed in mmol CO_2 fixed per mmol of photons absorbed (mmol CO_2/mmol photons)) in March showed the lowest yield (1.328) (Table 2), which was because the trees were beginning their leaf development, and the photosynthetic activity was small. The highest quantum yield was in May (4.870) and June (4.421), due to higher leaf development and the greater photosynthetic capacity of the leaves. The CO_2 assimilation rate decreased in August and September (Table 2), thereby reducing the orchard trees' quantum yield. A similar pattern was observed in the quantum efficiency, which represents the ratio of the energy used for CO_2 assimilation to the energy contained in the PAR absorbed by the canopy trees. The lowest quantum efficiency was observed in March (0.286 %) due to the lower leaf area of the trees. The highest quantum efficiency was observed in May (1.049 %) and June (0.952 %) (Table 2), which was due to greater leaf area and the greater photosynthetic capacity of the leaves. In August and September, the leaves began to lose their photosynthetic capacity, and their quantum efficiency decreased (Table 2). The observed quantum yield values are small, meaning that only a small proportion of the absorbed PAR is used for CO_2 assimilation. The rest of the PAR absorbed only causes thermal effects, which the trees must dissipate through high rates of foliar transpiration. As the quantum yield values of this study were obtained at the orchard level, and the tree's canopy only covered 16.4 % of the total surface, they were small compared to the values of previous studies, which were obtained at the leaf level. For example, Lombardini *et al.* (2009) reported that from June to August, Pawnee pecan

Table 2.: Average daily values per month of the quantum yield and quantum efficiency of a 7-year-old pecan nut orchard from Northern Mexico

Months	Quantum yield (μmol CO_2/mmol photons)	Quantum efficiency (%)
March	1.328^{d}	0.286^{d}
April	4.231^{b}	0.911^{b}
May	4.870^{a}	1.049^{a}
Jun	4.421^{ab}	0.952^{ab}
July	4.167^{b}	0.897^{b}
August	2.946^{c}	0.634^{c}
September	3.317^{c}	0.714^{c}

Means with different letters within the columns are different (Tukey, $\alpha \leq 0.05$)

Table 3: Integrated daytime and night-time NEE values of a pecan nut orchard (of 7 years old), during the growth months, and net assimilation retention (NAR)

Month	Daytime NEE (mmol/m^2)	Night-time NEE (mmol/m^2)	NAR (mmol/m^2)
March	398.05	689.47	1 087.52
April	-5 112.18	1 094.65	-4 017.53
May	-5 717.95	1 146.75	-4 571.20
Jun	-4 611.47	1 029.02	-3 582.45
July	-4 175.12	1 646.06	-2 529.06
August	-3 591.24	1 529.83	-2 061.41
September	-2 969.64	1 368.83	-1 600.81

trees' leaves highest quantum yield under direct solar radiation was around 12.5 µmol/mmol, and for the Stuart cultivar, for the same conditions, it was around 10 µmol/mmol. The quantum yield values of this study were also small compared to the values reported for plant ecosystems wherein the plant canopy covers the entire surface. In a forest ecosystem composed of a mixed patchy coniferous/deciduous forest located in Belgium, the quantum yield was 44 µmol/mmol (Carrara *et al.,* 2004). For a plantation of young rubber trees (*Hevea brasiliensis Müll*. Arg.), the quantum yield was 42.8 µmol/mol (Chayawat *et al.,* 2019). The quantum yield values observed in a vineyard (*Vitis vinifera L.*) in July (5.456 µmol/mmol) and August (4.118) (Zermeño-Gonzalez *et al.,* 2021) were similar to the values obtained in this study in May (4.870) and June (4.421).

Monthly balance of the CO_2 net ecosystem exchange

Because the orchard was made up of young trees (of 7 years old), most of the surface was bare soil or soil with little native vegetation, since the area of the tree's crown was only 16.4% of the total area. In March, the trees in the orchard were beginning to develop their leaf area, so most of the surface was bare soil, in such a way that the integrated daytime CO_2 NEE for the entire month resulted in a positive value of 398.05 millimoles per square meter (mmol/m^2), indicating that during daytime, the release of CO_2 was more significant than the assimilation (Table 3). For the months evaluated, the integrated night-time CO_2 NEE was positive, because at night, CO_2 release only occurs due to the nocturnal respiration of the vegetation and the soil surface (Table 3). For the months after March, the integrated daytime CO_2 NEE was negative, indicating a higher rate of CO_2 assimilation than of release. The highest integrated daytime CO_2 NEE was observed in May (-5 112.18 mmol/m^2), when the trees were in the most active stage of growth and fruit development; the trees allocated more photosynthates to fruit development, and fewer to wood growth (López and Arreola, 2008). The highest night-time CO_2 NEE was observed in July (1 646.06 mmol/m^2), which was probably due to the higher night-time temperature of the trees' leaves and soil, which increased the respiration rate of the soil–vegetation ecosystem (Flanagan and Johnson, 2005; Xu *et al.,* 2004). The pecan nut orchard's net CO_2 assimilation retention (NAR) was the difference between daytime and night-time CO_2 NEE. From March to September, the NAR was -17 274.94 mmol/m^2. April and May had the higher NAR with -4 017.53 mmol/m^2 and -4 571.20 mmol/m^2, respectively (Table 3). Considering that 46.4 % of the net assimilation of CO_2 is destined for the growth and formation of wood (Wang *et al.*, 2007, Negi *et al.*, 2003), this corresponds to 8 015.57 mmol/m^2, which equals 80 155.72 mol CO_2/ha, and corresponds to 0.962 t C/ha retained in the wood of the trees' orchard for the mentioned months. This value is lower than that observed by Wang *et al.* (2007) in pecan nut trees (Western Schley) of 12 m tall, wherein the total soil surface was shaded by the trees' canopy (10.24 t C/ha/y) in Las Cruces, N.M, USA. In pecan nut (*Carya illinoinensis (Wangenh.)* K. Koch) trees of 11 years old in a high-density plantation, the orchard carbon stock was 22.8 t C/ha, and the carbon assimilation rate was 1.67 t C/ ha/y (Yadav *et al.,* 2017). The atmospheric CO_2 assimilation values obtained in this study are small compared to those reported in other pecan walnut orchards and other woody tree species, because the trees were small and only covered 16.4% of the total area. However, during a large proportion of the growth months, carbon dioxide's assimilation is greater than its release, demonstrating that young pecan nut orchards, besides their economic and social importance, can also ecologically participate in the sequestration of atmospheric carbon to mitigate global warming. The peak daily values of NEE are observed around noon, and the peak monthly net CO_2 assimilation is from April to July. The main environmental factors contributing to these peaks are the incident solar photosynthetically active radiation, air temperature, relative humidity, and wind speed. In addition to exchanging CO_2 with the atmosphere, pecan nut trees and other plant ecosystems also exchange water vapor, oxygen, and other atmospheric gases. However, the scope of this study was only on the CO_2 exchange between the pecan nut orchard and the atmosphere. The potential limitations that may affect the CO_2 assimilation of a young pecan nut orchard are possible plant diseases that affect the leaves' growth, and adverse weather conditions that induce stomatal closure.

CONCLUSION

The rate of assimilation and the release of CO_2 from the pecan nut trees depends on the growth month. In March, the trees are just beginning their leaf development, and the orchard is a source of CO_2 released during daytime and night-time. The orchard is a sink for atmospheric CO_2 from April to September. The highest daytime CO_2 NEE assimilation rate corresponded to the peak rate of photosynthetically active radiation (PAR) absorption by the trees' canopy. It was observed between 11:00 and 14:00 during the day, throughout the growth months of the trees. The rate of assimilation being greater than the rate of release is attributable to the formation of carbon compounds that can be used for wood growth and fruit development. The CO_2 net ecosystem exchange values observed in this study are small, because the orchard was made up of young trees (of 7 years old) that had an average crown diameter of 4.78 m, which is equivalent to an area of only 15.75 m^2. This crown surface only covered 16.4% of the total soil surface. The relationship between the CO_2 net ecosystem exchange and the photosynthetically active radiation (PAR) absorbed by the trees' canopy (an average of 30 min) through the growth months was described using a rectangular hyperbolic function. This function depicts an increase in NEE as the absorbed PAR increases. The orchard's highest yield and quantum efficiency were observed in May, the month with the highest net assimilation of CO_2. Despite the young age of the trees, the orchard has a retention capacity of 0.962 t C/ha for the months evaluated. The orchard sequestration capacity will increase with the growth of the trees due to a greater total leaf area and greater biomass development. Therefore, due to their condition of woody and long-living plant species, pecan nut trees, in addition to their use for walnut production, may play an essential role in CO_2 assimilation and atmospheric carbon sequestration, thereby significantly contributing to society.

AUTHOR CONTRIBUTIONS

A Zermeño-González performed the experimental design, analysis, and interpretation of the data, and prepared the manuscript. E. Jiménez-Alcala participated in the field study, data collection, and literature review. J. Gil-Marín contributed to the literature review, manuscript preparation, and editing. H. Ramírez helped in the literature review and manuscript preparation. M. Cadena assisted in the field study, data collection, and analysis. A. Melendres contributed to the field study, sensor calibration and operation, and data collection.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest regarding the publication of this manuscript. In addition, no ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, or redundancy, have been observed by the authors.

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ABBREVIATIONS

α	Alpha
%	Percent
$\Delta\rho CO_2$	Change of density of carbon dioxide
Δt	Time segment
Δz	Height above the ground surface
$\mu mol\ CO_2/m^2/s$	Micromoles of carbon dioxide per square meter per second
$\mu mol\ photon/m^2/s$	Micromoles of photons per square meter per second
$\mu mol\ CO_2/mmol\ photon$	Micromoles of CO_2 per mmol of photons
ρco_2	Density of carbon dioxide
3-D	Three-dimensional
b1	Highest photosynthetic capacity of the ecosystem
b2	Photosynthetically active radiation of the mean value of the photosynthesis rate
b3	Daytime respiration rate of the ecosystem
CO_2	Carbon dioxide
cm	Centimeter
°C	Degrees Celsius
E	Energy
FCO_2	Carbon dioxide flux
ha	Hectare
H_2O	Water
Hz	Hertz
LPH	Liters per hour
m	Meter
masl	Meters above sea level
$mmol/m^2$	Milimol per square meter
min	Minutes
MJ	10^6 joules
m/s	Meter per second (velocity unit)
m^2	Meter square
NEE	Net ecosystem exchange
nm	Nanometer
PAR	Photosynthetically active radiation
$Quant_{yield}$	Quantum yield
$Quant_{Eff}$	Quantum efficiency
s	Second
t	Ton
t/ha	Tons per hectare
TC/ha	Tons of carbon per hectare
$t/CO_2/ha/y$	Tons per carbon dioxide per hectare per year
w	Vertical wind speed

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SPECIAL ISSUE: Eco-friendly sustainable management

Original Research Article

Life cycle assessment of paper products based on recycled and virgin fiber

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ABSTRACT

BACKGROUND AND OBJECTIVES: Virgin wood fiber and recycled waste paper are the main raw materials for paper production. Virgin wood-fiber paper appears less favorable than recycled paper, as recycled paper generally consumes more natural resources. globalThis study presents a comparative life cycle assessment of paper production in Indonesia using wood fibers and recycled fiber materials. This life cycle assessment study aimed to compare two comparable products, namely duplex board with 93 percent recycled fiber and folding boxboard with 100 percent wood or virgin fiber raw materials.

METHODS: Both products were represented as one metric ton of the final product. The study utilized a cradle-to-grave system and combined primary data from a paper factory in Indonesia with secondary data from the Ecoinvent database, representing processes in background systems. Various impact assessment methods were employed to evaluate the environmental impact, including the Greenhouse Gas Protocol, the Centre for Environmental Studies, International Reference Life Cycle Data System, and the United Nations Environment Program, Society for Environmental Toxicology, and Chemistry toxicity model. All inventory and impact assessments were performed using SimaPro software.

FINDINGS: The current study revealed that duplex board is environmentally preferable to folding boxboard across all the impact categories assessed. The results of the impact assessment of global warming potential fossil, acidification, particulates, fossil abiotic depletion, and human toxicity-cancer for duplex board were 1,848.26 kilogram carbon dioxide equivalent, 8.12 kilogram-sulfur-dioxide-equivalent, 2.12 kilogram particulate matter 2.5-equivalent, 14,668.06 megajoule, and 0.0000017 comparative toxic unit, while for folding boxboard 2,651.25 kilogram carbon-dioxide-equivalent, 13.95 kilogram sulfur-dioxide-equivalent, 3.27 kilogram particulate matter 2.5-equivalent, 22,395.81 mega-joule, and 0.0000021 comparative toxic unit, respectively. All impact magnitudes were measured in functional units per 1 ton of paper product.

CONCLUSION: The study has revealed the environmental impact of paper products produced in Indonesia. Paper products made from recycled fibers are a more environmentally favorable option when than those produced from virgin fibers. Through further contribution analysis, it was determined that the main contributor to all impact categories in both production systems was fossil-based energy input. Efforts to improve the environmental performance of the two products should focus on enhancing the energy efficiency of the system and incorporating non-fossil fuel energy sources into the production process.

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INTRODUCTION

Pulp and paper production produces approximately one million tons of waste annually (Kinnarinen *et al*., 2016). Various organic and inorganic wastes, such as coal ash, dregs from green liquor, slaker grits, lime mud, and sludge from wastewater treatment, are produced during the pulp and paper manufacturing process. Improper handling of these wastes substantially impacts the environment negatively, lowering the quality of water, soil, and air (Simão *et al*., 2018; Kusumawati and Mangkoedihardjo, 2021; Brotosusilo *et al.* 2022; Hazbehiean *et al.* 2022). Wastewater emission is created during washing, recovery, and preparation of raw materials (Song *et al*., 2019). Solid waste is sourced from the wastewater filtration process, sludge from the wastewater treatment process, and sludge from chemicals (Durdević *et al*., 2020; Le Dinh *et al.* 2022; Sivakumar *et al.* 2022; Maphosa and Maphosa, 2022). Solutions aiming to reduce the amount of waste produced are required to achieve sustainability and reduce the negative effects of ongoing paper production. The amount of paper produced has increased from 404 million tons in 2014 to 409 million tons in 2018. Most of the waste paper was recycled to produce paper products. The recovery rate, called the amount of paper collected for subsequent use in producing paper, is approximately 56 percent (%). Globally, there are 229 million tons of recycled paper. China is the world's largest paper producer, followed by the United States, Japan, Germany, and India (FAO, 2019). According to Statistic Indonesia, statistics for the growth of the paper production index rose from 1.43 in 2010 to 4.01 in 2019 (BPS, 2021). According to a forecast of paper products published by Fastmarkets, global paper consumption is expected to increase by 40% in 2028, while recycled paper consumption is expected to rise by 64% (WBCSD, 2015). Except for tissue products, whose consumption is currently increasing, several paper products are predicted to decline due to advancements in digital technology. The primary step in producing paper involves extracting fibrous raw materials to create pulp, which is then processed to create paper products. Virgin wood fibers and recycled paper are the two main raw materials used to make paper (Grossmann *et al.,* 2014). The pulp comprises lignocellulosic materials, such as wood or other processed materials. Producing virgin wood fibers starts with wood cut into logs or chips. Then, the pulp can be obtained through mechanical or chemical processes. A network of pulp fibers was created by dispersing the fibers in water. The pulp is prepared and further processed according to the type and quality of the paper required for the production process (Bajpai, 2015). The recycled fiber's main raw materials comprise waste paper from commercial, institutional, and domestic activities that are collected, refined, and sorted to create waste paper, and then recycled as a raw material for paper products. Recycled fiber production begins with the waste paper pulping process, in which the incoming paper is wetted and fragmented into separate fibers, followed by mechanical contaminant removal with or without ink removal, and a bleaching process (WBCSD, 2015). Since fibers lose quality with each recycling cycle, they cannot be recycled indefinitely (Gavrilescu *et al*., 2012). Recycled paper is crucial to people's economic activities, integrally forming the circular economy concept. In a circular economy scheme, the final stages of the product life cycle link to production by reutilizing the resources contained in the used products. This approach is particularly well-suited for the pulp and paper industry as it allows producing paper and packaging materials using recycled paper products (WEF, 2016). Recyclable waste paper can be used for various paper products, such as napkins, newspapers, office and printing paper, cardboard boxes, envelopes, wrapping paper, wallpaper, egg packaging, etc. Research has demonstrated that recycling can stimulate the development of new economically viable products (Ozola *et al.,* 2019). Utilizing recycled paper offers several advantages compared to using virgin fiber materials when considering the environmental impact of the process. Using recycled paper helps preserve the environment and conserve natural resources by reducing the number of trees harvested, minimizing air pollution, and consuming less energy (Bajpai, 2014). Recycled paper occasionally exhibits higher greenhouse gas (GHG) emissions than virgin fiber paper because virgin fiber utilizes biomass from the pulping process to produce energy. Acknowledging that recycled paper generally has lower quality than paper made from virgin fibers is also important because the quality of the paper degrades with each recycling cycle. Recycled paper typically can be recycled five to seven times (WBCSD, 2015). The need for environment-friendly products is becoming increasingly recognized (Alamsyah *et al.,* 2020). Thus, evaluating the comprehensive environmental impact of paper products made from virgin fibers and recycled fibers is crucial to provide considerations on environment-friendly products. In response to concerns about the environmental impact, environmental product certification programs have been established encompassing product quality and its environmental aspects. The Indonesian government has enforced this certification through standards and regulations. The ecolabelling scheme in the Indonesian National Standard (SNI) criteria mandates using recycled raw materials in various products, such as paper, plastic shopping bags, and other items. In line with environmental goals, Indonesia has committed to reducing greenhouse gas (GHG) emissions. As stated in the Nationally Determined Contribution document, Indonesia aims to achieve a 29% from the baseline of 2010 by 2030 (Suroso *et al*., 2022). The target is divided into categories, including forestry, energy, waste management, use of industrial goods and processes, and agriculture (Malahayati and Masui, 2021). Life cycle assessment (LCA) is one of the methodologies used to determine how an activity, process, or product impacts the environment (Drobyazko *et al.,* 2021). LCA is a technique used to evaluate the product life cycle from start to finish. It provides a comprehensive evaluation of each stage, starting from the collection and processing of raw materials to the product's use by consumers. The LCA study presented in International Organization for Standardization (ISO) 14040: 2006 comprises four main steps: defining the purpose and range of the investigation, building a product life cycle model with all environmental inputs and outputs or a life cycle inventory, evaluating the life cycle impact, and interpreting the investigation (Pryshlakivsky and Searcy, 2013). LCA is widely recognized as a recommended technique for examining the environmental effects of paper products, particularly in European countries. It is standardized in the Intermediate Paper Product Product Environmental Footprint Category Rules (PEFCR) for intermediate paper products. This is also acknowledged in the environmental product declaration standard in the global scheme for various types of final paper products (Schau, 2019). The latest LCA research focusing on paper products from virgin wood and recycled fiber conducted in China showed that virgin wood fiber-based paper had a higher impact than the recycled paper on most categories assessed except respiratory organics, respiratory organics, non-carcinogens, terrestrial ecotoxicity, aquatic ecotoxicity, aquatic eutrophication and terrestrial acidification (Hong and Li, 2012). Another study on paper products found in various countries; in Brazil, a life cycle impact assessment was conducted on offset paper products based on virgin wood fiber (Silva *et al*., 2015); in China, a similar assessment was applied to a corrugated box of delivery packages which based on the mix of virgin wood and recycled fiber (Yi *et al*., 2017); in Singapore, LCA applied on kraft paper of grocery bags (Ahamed *et al.*, 2021); in Portugal, LCA conducted for pulp and paper companies which based on virgin wood fiber (Santos *et al.*, 2018). None of the comprehensive (cradle-to-grave scope) environmental impact or LCA research on paper products is found in Indonesia. This is another important reason why it was necessary to carry out this study. This study aimed to evaluate the potential environmental effects of abiotic depletion—fossil fuel, acidification, climate change—fossil emissions, particulates, and human toxicity–on paper production from virgin wood fibers and recycled fibers using LCA. The study was conducted at X factory in Indonesia in 2022.

MATERIALS AND METHODS

The study was conducted at X factory in Indonesia, focusing on two specific types of paper products: folding boxboards (FB) and duplex boards (DB). DB paper is a multi-layer board fully coated on top to meet the application requirements of multi-purpose packaging boards. FB is made from a single layer used for packaging light products. The FB in this study was made of 100% virgin fiber, and the DB was made of 93% recycled fiber and 7% virgin fiber. Both paper types are used as packaging materials with white-colored characteristics. The assessment also included wastepaper material supplier and the pulp material, Leaf Bleached Kraft Pulp (LBKP), produced by two Indonesian pulp mills known as pulp-1 and pulp-2. The data collection period is one year with monthly data records for materials, production, solid waste and wastewater emission, and semester data records for air emission. Primary data for inventory purpose were collected based on process charts of the production process observed based on the input and output processes recorded by manufacturing company. Primary data includes raw material consumption, production, and emission of X factory, pulp-1, pulp-2, and waste paper supplier. Primary emission data comprises (a) air emissions, such as sulfur oxides, nitrous oxides, particulates, and hydrogen sulfide; (b) wastewater emissions, such as chemical oxygen demand (COD), biological oxygen demand (BOD), absorbable organic halides (AoX), total suspended solid (TSS), and other substance; (c) solid waste emission, such as sludge, ash, dregs dan grits. All substance emissions are measured by third-party laboratories. The consistency of the input and output data was checked by mass balance, and a data quality check was performed according to the ISO requirements in ISO 14044: 2006 (Klöpffer, 2012). To assess the energy consumption throughout the production process, an energy balance was established. This provided an overview of the fuel inputs and its conversion into energy, such as electricity and steam, which were subsequently distributed to various users within the factory. Additional data for this study were obtained from the Ecoinvent database integrated with SimaPro software, the Intergovernmental Panel on Climate Change (IPCC), and other relevant reference sources. Raw material extraction, processing, and emission are obtained from secondary data, the Ecoinvent database. Carbon dioxide and other GHG of X factory, pulp-1, pulp-2, and wastepaper supplier are obtained from IPCC emission factors. Data processing and exposure analysis were performed using the SimaPro software (Herrmann and Moltesen, 2015) with cradle-to-grave stages. Environmental impact analysis is carried out according to the general LCA framework, which consists of four steps: defining the purpose and scope, analyzing the inventory data by production stages, assessing the impact, and interpreting the results. Targeting and scoping were performed to determine the boundary of the inventory data search, and inventory data were collected along with input and output data for each period. Data collection included input and output information for each stage, and inventory data were analyzed to calculate environmental impacts. The final step involved interpreting the results, which included identifying significant impacts and evaluating the findings. The functional unit of the study was one ton of paper used as a packaging material. All data obtained on the raw materials, activities, stages, processes, and system flows were included in the scope of the study. This study applied a zero-burden impact to recycled paper discarded by the user. The scope of this study was the cradle-to-grave period, as shown in Fig. 1. The stages are divided into four sub-stages: (A) cradle sub-stages, comprising wood material extraction and the collection and pre-treatment of waste paper; (B) gate-pulp sub-stages, comprising LBKP pulp production at pulp-1 and pulp-2 factories, Needle Bleach Kraft Pulp (NBKP) material, Bleached Chemi-Thermomechanical Pulp (BCTMP) material, and deinking pulp production at X factory; (C) gate-paper sub-stages, comprising paper manufacture at X factory; and (D) grave sub-stages, comprising product distribution and disposal. Assessment of the potential environmental impact focuses on the high potential impact as estimated by PEFCR, namely abiotic depletion potential-fossil fuel (ADP-f), acidification potential (AP), climate change due to fossil emissions through global warming potential (GWP-f), and particulate matter on fine particlulate ($PM_{2.5}$), with the addition of human toxicity-cancer (HTC). The potential environmental impact is quantified using Simapro software. The SimaPro software works to produce life cycle inventory results, containing elementary flows representing emissions or extractions of the environment. Each elementary flow is assigned to impact categories, such as global warming potential (GWP), AP, $PM_{2.5}$, ADP and HTC, based on substances contained in elementary flow contributing to the environment. The characterization model of the climate change impact uses the GHG protocol of the World Resources Institute and World Business Council for Sustainable Development (WBCSD) (GGP, 2023), which adopts a characterization model based on the latest Intergovernmental Panel on Climate Change (IPCC) on fossil fuels and GWP for 100 years in kilogram (kg) carbon dioxide equivalent (CO_2 eq) (IPCC, 2023). Gaseous emissions included in the study were carbon dioxide (CO_2), methane (CH_4), nitrous oxide, hydrochlorofluorocarbons

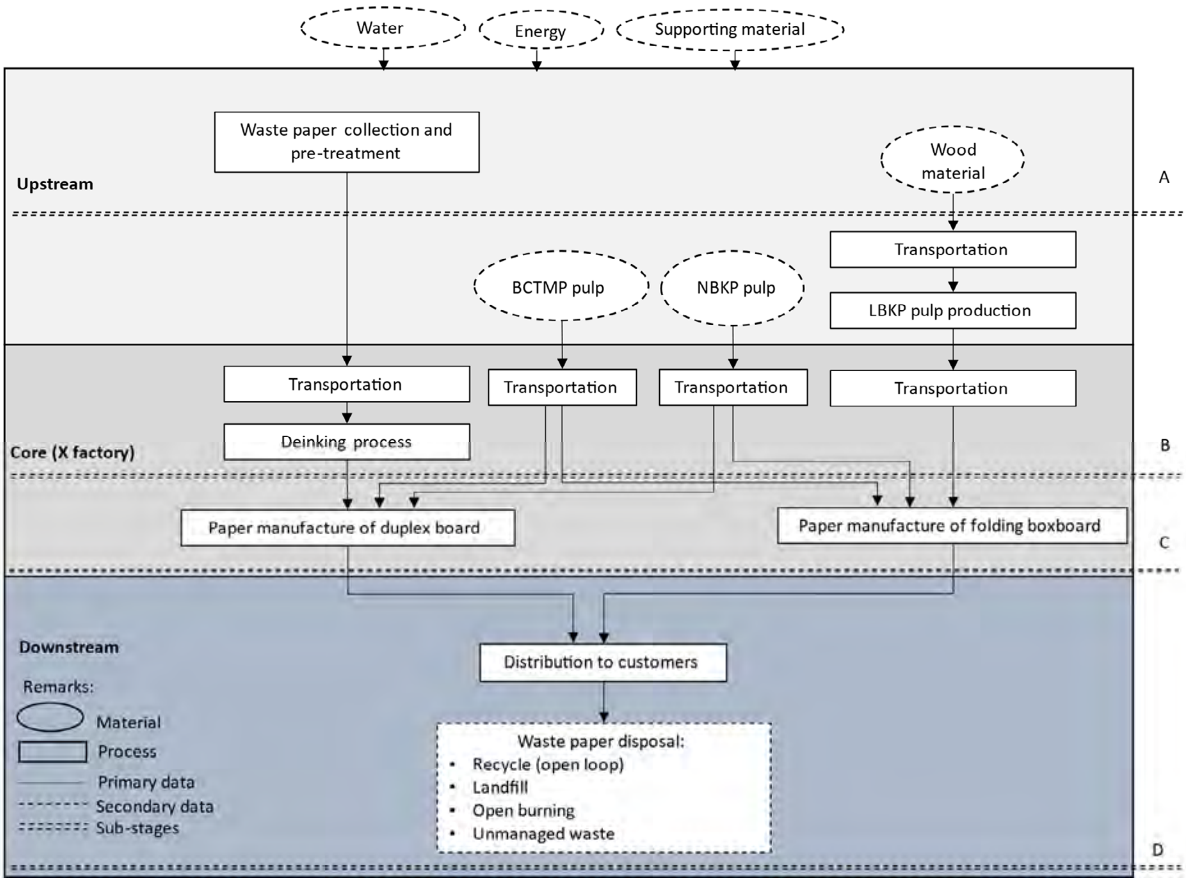

Fig. 1: Scope of life cycle stages of the study from cradle to grave

(HCFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride. ADP uses the Center for Environmental Studies (CML) model with characterization factors in megajoule (MJ) fossil energy carriers with low heating values (van Oers and Guinée, 2016). The AP uses CML that adopts the Regional Air Pollution Information and Simulation (RAINS) 10 model (Huijbregts *et al.,* 2003) with a characterization factor in kilogram sulfur dioxide equivalent (kg SO_2 eq). Emission substance impacting AP includes sulfur dioxide, nitrogen dioxide, hydrogen chloride, hydrogen sulfide, hydrogen fluoride, ammonia, nitric acid, phosphoric acid, sulfuric acid, and sulfur trioxide. $PM_{2.5}$ uses the International Reference Life Cycle Data System (ILCD) 2011 Midpoint+ with a characterization factor of $PM_{2.5}$ intake fraction in kg $PM_{2.5}$ eq unit (Humbert *et al*., 2011). The HTC uses the United Nations Environment Program, Society for Environmental Toxicology and Chemistry toxicity model (USEtox) with characterization factors in the comparative toxic unit for humans (CTUh) or cases/kg emissions (Rosenbaum *et al*., 2008). After the impact assessment result related to the inventory process, goal, and scope definition was interpreted, the significant contribution (hotspot) of stages and inventory was identified.

RESULTS AND DISCUSSION

Life cycle inventory was applied to all life cycle stages to identify the input and output process of the product system, including the inventory of waste paper collection and pre-treatment at supplier, virgin pulp production, deinking pulp production, paper production, distribution, and product disposal. The impact assessment was then performed to measure the impact magnitude of each life cycle stage, focusing on GWP-f, ADP-f, AP, $PM_{2.5}$, and HTC impact. The impact result was interpreted to analyze the significant contributors of stages and inventory process.

Life cycle inventory

Inventory data for stage A, namely wood extraction, waste paper collection, and pre-treatment. The inventory process of wood materials was obtained from secondary data from the Ecoinvent database. The general description of wood production in Ecoinvent secondary data includes wood nurseries, forest clearing, wood management, and timber harvesting (de la Fuente *et al*., 2017). Secondary data on wood production were aligned with the actual conditions of the wood supplier, namely eucalyptus wood, with a sustainable forest management system (Schulte *et al.,* 2021). The process of collecting and pre-treatment wastepaper at the supplier's factory involves several steps. The wastepaper is collected from various sources by collectors. The collected wastepaper is then transported from the collectors to a warehouse in the relevant regional capital. The wastepaper is further transported to the wastepaper pre-treatment center. At the pre-treatment center, the wastepaper is separated from other materials, such as plastic and other waste. The wastepaper is then compressed using a ball press machine. This process turns wastepaper raw material into compressed bales, which can be readily supplied to factory X for further processing. The input stream comprises the transportation of wastepaper from collectors to suppliers, wire as a binder, and electricity consumption. The output stream comprises the production of recycled raw materials. One ton of wastepaper output needs 0.03 tons, 10 Kilowatt-hour (KWh), and 1071 ton. kilometers (ton.km) of wires, electricity, and material transportation, respectively. X Factory uses three types of virgin pulp produced in stage B: LBKP pulp with hardwood raw materials, NBKP pulp with softwood raw materials, and BCTMP pulp with long or short fiber materials. NBKP and BCTMP pulps were imported from abroad. Primary data observation was conducted for LBKP pulp production because LBKP pulp is produced in Indonesia by two suppliers: pulp-1 and pulp-2 mills. The LBKP pulp-production process is illustrated in Fig. 2. The LBKP pulp production starts with wood preparation, which consists of removing the bark, chipping to cut the wood into chips, and a screening process to separate oversize chips. The separated bark is utilized as fuel to produce energy. The chips were then cooked in a digester using white liquor chemicals to dissolve and separate lignin. The output of this digester is dissolved pulp fiber and cooking residual liquid called black liquor. Black liquor, a by-product of cooking, is fed into the evaporator to produce heavy black liquor. It is then sent to the recovery boiler to obtain green liquor and steam, which the

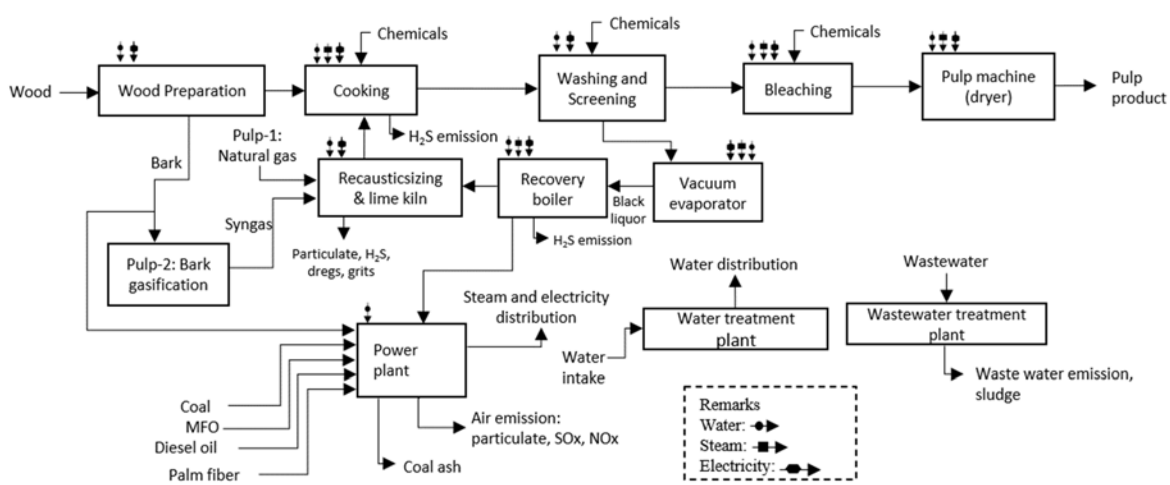

Fig. 2: Flow diagram of production process of pulp production in pulp-1 and pulp-2 factory

latter used as a fuel source to produce steam and electricity. The green liquor is then fed to the lime cycle, the recausticizing process, and the lime kiln to produce white liquor, a chemical used in the cooking process in the digester. The fiber formed from the digester was then washed and screened to separate unwanted dissolved materials, such as knots, debris, sieve, and other impurities. The pulp undergoes a delignification process to reduce lignin levels using heat and chemicals, followed by a bleaching process to remove impurities, eliminate residual lignin, and obtain a high brightness level. The bleached pulp is then sent to the pulp machine, where screening, dewatering, and drying processes are performed to produce pulp sheets, the end product of the pulping process. The difference in the pulp-production process between the suppliers of pulp-1 and pulp-2 lies in the use of gas in the lime kiln; the pulp-1 uses natural gas, whereas pulp-2 uses syngas derived from bark gasification. The raw material input data comprised wood primary raw material for pulp production sent from industrial plantation forests, supported by water and chemicals, such as caustic soda, sulfur dioxide, chlorine dioxide, oxygen, sodium oxide, hydrogen peroxide, defoamer, talc, and hydrochloric acid. The energy data input for the LBKP pulp production includes steam and electricity from power generation, natural gas, and oil fuel. The product flow output data include pulp products as the main product to be sold and side products, such as bark and black liquor. These side products are valuable biomass recyclable into energy. The mass balance data for mainstream products are listed in Table 1. Supporting materials and energy were added to support the production process. Additional data input for supporting materials includes heavy fuel as fuel for lime kilns, diesel oil, and gasoline for transportation within the factory, chemicals for water treatment and wastewater treatment, and refrigerant for miscellaneous. The emission output data included wastewater, solid waste, and air emissions. Pulp-1 and pulp-2 mills have the same energy-generation processes. Both factories have multi-fuel boiler facilities using coal, fuel oil, and bark as fuel and recovery boilers using black liquor. The fossil fuel proportion for energy generation of pulp-1 and pulp-2 are 31% and 3%, comprising coal and fuel oil, respectively. The pulp-1 mill produces more various products with higher product capacity than the pulp-2 mill; as a result, the former needs more fossil fuel to fulfill energy needs. The bark is a side product of the initial pulp processing process, whereas black liquor is derived from the pulp cooking and washing process. Black liquor and bark are categorized as usable biomass fuels to substitute coal. The proportion of these two fuels is very high, which can reduce carbon emissions from fossil fuels. Water treatment is used to process water intake from the river to produce clean water, whereas wastewater treatment is used to process wastewater before disposal to the river (Nimesha *et al*., 2022; Moghadam and Samimi, 2022). Other

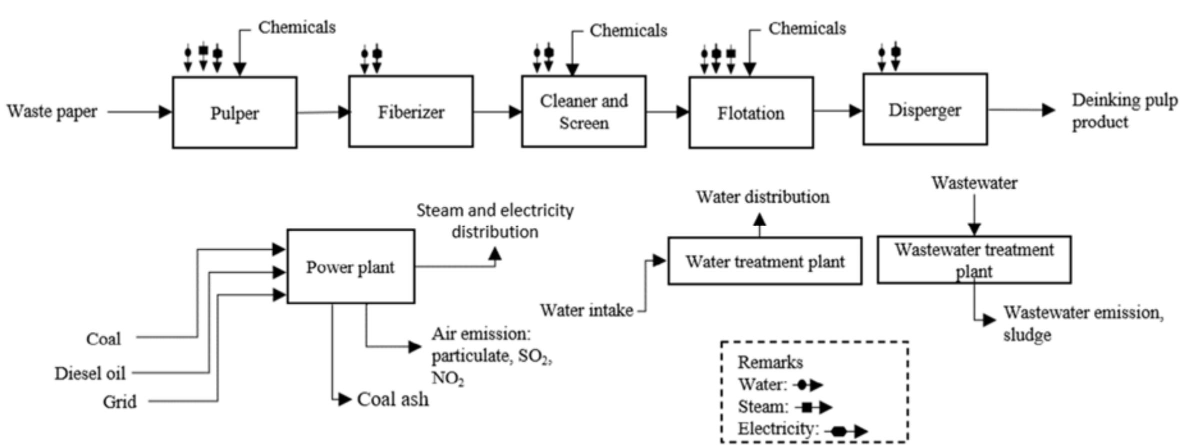

Fig. 3: Flow diagram of deinking pulp production in X factory

Table 1: Inventory data of LBKP pulp production in pulp-1 and pulp-2, and deinking pulp production in 1 ton of pulp product

Process flow	Unit	Amount		
		LBKP Pulp-1	LBKP Pulp-2	Deinking pulp
Input:				
Wood	Ton	3.6373	3.4188	1.2900
Waste paper	Ton	-	-	
Chemical for production	Ton	0.0667	0.0695	0.0731
Chemical for water treatment	Ton	0.0066	0.0014	0.0013
Chemical for wastewater treatment	Ton	0.0041	0.0009	0.0013
Natural gas	Ton	97.6865	-	-
Refrigerant	Ton	0.0025	0.0005	-
Coal	Ton	0.4249	0.0182	0.2624
Black liquor	Ton	0.4281	0.3523	-
Palm fiber	Ton	1.7231	1.4040	-
Marine Fuel Oil fuel	Ton	0.0311	-	-
Diesel oil	Ton	1.0565	7.0611	0.0829
Air	Ton	1.2491	5.5252	17.1906
Diesel oil for vehicle	Ton	33.0713	21.2062	-
Gasoline for vehicle	Ton	0.0480	0.4350	-
Transportation	Ton	0.0078	0.0190	3,812.61
Output:				
Pulp production	Ton	1.0000	1.0000	1.0000
Black liquor	Ton	1.7231	1.4040	
Bark	Ton	0.4281	0.3523	
Emission:				
Liquid waste, volume	Ton	23.5574	10.9890	13.2934
Liquid waste, COD	Ton	0.0061	0.0021	0.0022
Liquid waste, BOD	Ton	0.0016	0.0006	0.0005
Liquid waste, AoX	Ton	0.0000	0.0000	0.2043
Sludge	Ton	0.0084	0.0005	13.2934
Liquid waste, TSS	Ton	0.0017	0.0233	0.0003
Air emissions, $PM_{2.5}$	Ton	0.0002	0.0000	0.00002
Air emissions, PM_{10}	Ton	0.0001	0.0000	0.00001
Air emissions, $PM_{>10}$	Ton	0.0005	0.0000	0.0001
Air emissions, SO_2	Ton	0.0012	0.0001	0.0003
Air emissions, NO_2	Ton	0.0006	0.0005	0.0010
Air emissions, H_2S	Ton	0.0000	0.0000	-
Solid waste, Ash	Ton	0.0592	0.0008	0.0130
Solid waste, Dregs and grits	Ton	0.0218	0.0031	-

materials, such as packaging and refrigerants, are used to support production activities. Deinking pulp production for DB products occurs in X Factory at the stock preparation stage. Waste paper is the primary raw material for producing DB products. Pulp-making processes from wastepaper comprise two types: without deinking and with deinking. DB products require a deinking process because of the need for white color on the outside. The types of waste paper in the deinking process are shorted white ledgers, shorted office paper, old newspapers (ONP), and old magazines (OMG). All types of waste paper can be processed for pulp without deinking. Producing pulp without the deinking process begins with the pulper process crushing and dissolving wastepaper, and then feeding to the detrasher to separate impurities. The process continues with filtering and cleaning using a screen, followed by compaction in a thickener. The milling process takes place in a refiner to obtain fine fiber pulp, then sent to the paper-making machine for further processing into paper. Meanwhile, manufacturing deinking pulp begins with crushing and dissolving wastepaper in the pulp stage, followed by fiber grinding using a fiberizer. The mixture then undergoes filtration and separation of impurities through screens and cleaners. Hydrophobic materials, such as ink and toner, are released in a flotation process, and further cleaning is performed in a cleaner. The final stage involves ink removal in the disperger. These processes produce deinking pulp, which is then fed into the paper-making machine. The input data comprised the waste paper, chemicals, and water. The chemicals used included hydrogen peroxide, sodium hydroxide, sodium metabisulfite, and some minor chemicals. The output data comprised the deinking pulp products, wastewater, and sludge. The deinking pulp flow diagram is shown in Fig. 3.

FB and DB paper production in stage C occurs in X factory but in separated lines of paper machines. Fig. 4 illustrates the FB paper production process, while Table 2 presents the product flow data for paper production. Paper production starts from mixing the pulp materials, chemicals, and water in the stock preparation. The product is then fed to the wire part to remove water and form paper. Next, the paper flow was pressed to remove excess water and then dried in the dryer system. After forming the paper sheet, a coating process is applied to obtain cardboard sheets, as customers require. These sheets are then sent to the conversion process to form cardboard shapes according to the customer's specifications. The FB paper production process takes place in four main parts: stock preparation, wire, dryer, coater, reel, and winder. The input data for the folding boxboard paper products comprise LBKP pulp, NBKP pulp, BCTMP pulp, chemicals, and water. The chemicals used include alkyl ketene dimer sizing agents, starch, retention aids, dyes, calcium carbonate, aluminum chloride, coatings, and other minor chemicals. The output data comprised the FB paper products, wastewater emissions, and sludge. DB paper is generally produced like that for FB; however, they only differ in raw materials and specific chemicals. The input data included waste paper, NBKP pulp, BCTMP pulp, chemicals, and water. The output data included the DB paper products, wastewater emissions, and sludge. The chemicals used were alkyl ketene dimer sizing agents, starch, retention aids, dyes, calcium carbonate, aluminum chloride, coatings, and other minor chemicals. FB and DB paper production use electricity and steam generated from an energy generator (power plant) owned by X Factory and a small portion of the purchased electricity from the grid. The main generator is a coal boiler producing steam and electricity, called co-generation. A generator set powered by diesel oil fuel and low-pressure steam from biogas is added to support energy needs. The biogas energy generator produces low-pressure steam from burning methane gas derived from anaerobic wastewater treatment. In addition, to using captive energy, factories use small amounts of electricity from the grid. The fossil fuel proportion of X factory for power generation is 96% comprising coal and fuel oil. The X factory is highly dependent on fossil fuels due to the limited source of renewable energy on the island where the factory is located.

The product distribution and disposal are included in stage D. The transportation of FB and DB products from X Factory to customer location is modeled at the most extensive customer. Two primary modes of transportation are involved: road and sea transports. Freights by road calculates at 7,463,150 ton.km and by sea at 247,179,528 ton.km. The mass balance of disposal was obtained from secondary data provided by the Ministry of Environment and Forestry through the National Waste Management Information System (SIPSN, 2020). The percentages of managed and unmanaged waste in 2020 are 76.89% and 23.11%, respectively. The managed waste comprised 24.7% recycling, 5% open burning, 10% managed landfill, and 37.19% residue at the unmanaged landfill.

Life cycle impact assessment

The results of the impact assessment of the two study products using the LCA method are presented in Table 3. The impact results show that FB paper has the higher environmental impact than DB paper across all the analyzed impact categories. The GWP-f, ADP-f, AP, $PM_{2.5}$, and HTC impact of FB paper was higher at 43%, 53%, 72%, 54%, and 21%, respectively, than that of DB paper.

In previous research conducted in Brazil, the impact of GWP-fossils and acidification for offset paper products from the virgin fiber are 1,050 kg CO_2 eq and 10.6 kg SO_2 eq with a functional unit of 1 ton of paper products produced (Silva *et al*., 2015). In China, the GWP and acidification impact of corrugated box products is 0.754 kg CO_2 eq and 4.83 kg SO_2 eq for a functional unit of 0.16 kg of corrugated box products (Yi *et al*., 2017), and the particulate, $PM_{2.5}$, of writing paper for paper from virgin fiber and recycled is 0.624 kg $PM_{2.5}$ eq and 0.458 kg $PM_{2.5}$

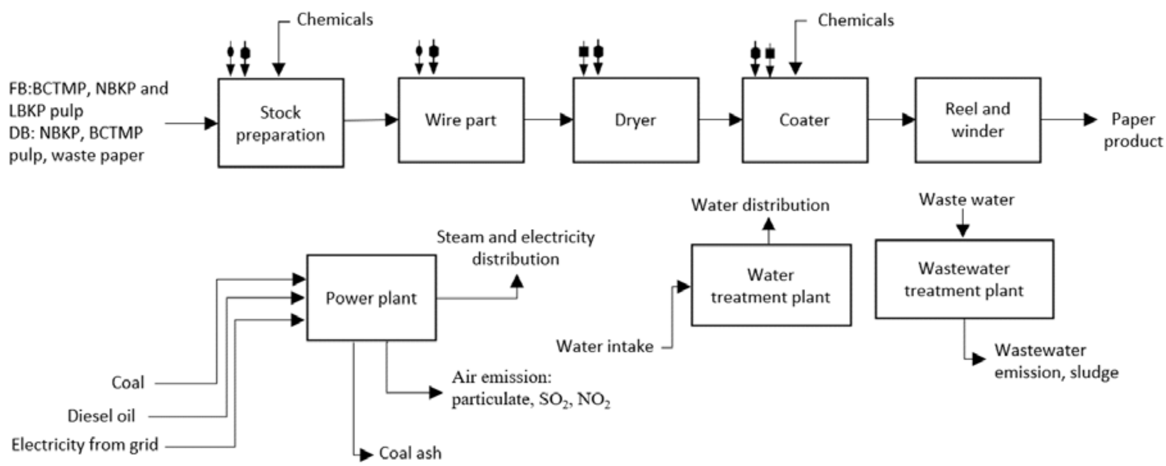

Fig. 4: Flow diagram of FB and DB paper production in X Factory

Table 2: Data inventory of FB and DB paper production in 1 ton paper product

Inventory process	Unit	FB	DB
Input:			
Pulp of LBKP pulp-1	Ton	0.1477	-
Pulp of LBKP pulp-2	Ton	0.1477	-
Deinking pulp	Ton	-	0.205
NBKP pulp	Ton	0.0774	0.031
BCTMP pulp	Ton	0.4234	0.015
Waste paper	Ton	-	0.470
Chemicals	Ton	0.2192	0.310
Chemicals for water treatment	Ton	0.0010	0.0009
Chemicals for wastewater treatment	Ton	0.0009	0.0008
Refrigerant	Kg	0.0020	0.0020
Materials for converting (ink, plastic wrap, strapping, glue, pallet)	Ton	0.0005	0.0005
Coal	Ton	0.5235	0.508
Diesel oil	Liter	0.1654	0.161
Biogas	m^3	0.8711	0.846
Electricity from grid	MWh	0.0953	0.093
Water	m^3	12.2496	11.146
Transportation	Ton.km	6,409	2,700.575
Output:			
Paper product	Ton	1	1
Emission:	Ton		
Liquid waste, volume	Ton	9.4726	8.619
Liquid waste, COD	Ton	0.0017	0.002
Liquid waste, BOD	Ton	0.0004	0.0004
Sludge	Ton	0.1456	0.132
Liquid waste, TSS	Ton	0.0002	0.0002
Air emissions, $PM_{2.5}$	Ton	0.0000	0.00004
Air emissions, PM_{10}	Ton	0.0000	0.00002
Air emissions, $PM_{>10}$	Ton	0.0001	0.0001
Air emissions, SO_2	Ton	0.0005	0.001
Air emissions, NO_2	Ton	0.0020	0.002
Solid waste, Ash (coal ash)	Ton	0.0260	0.025

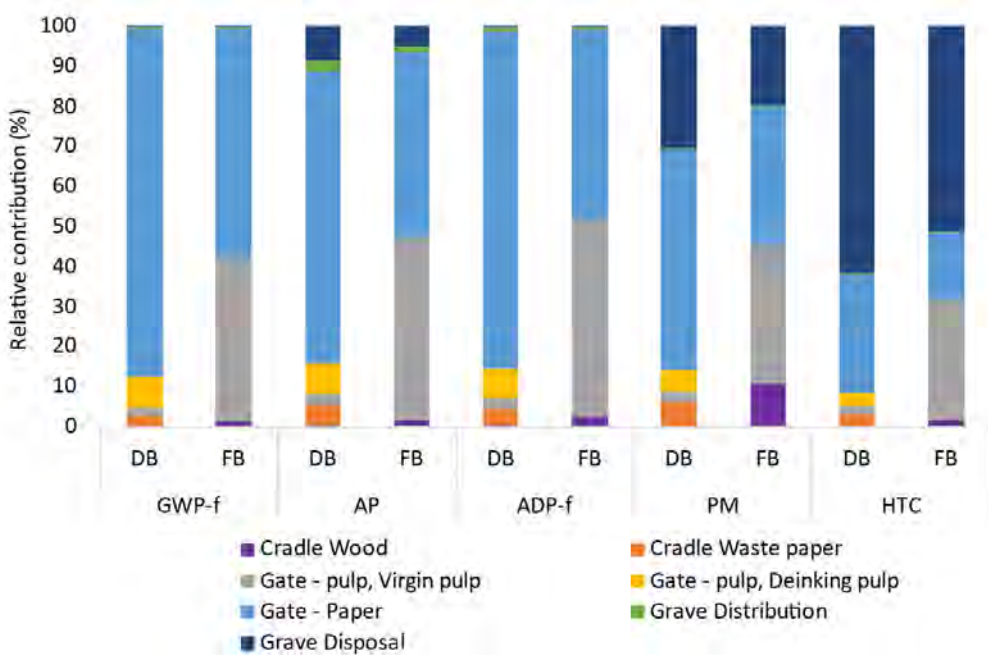

Fig. 5: Relative contribution of each stages on impact result of FB and DB paper production

further cleaning is performed in a cleaner. The final stage involves ink removal in the disperger. These processes produce deinking pulp, which is then fed into the paper-making machine. The input data comprised the waste paper, chemicals, and water. The chemicals used included hydrogen peroxide, sodium hydroxide, sodium metabisulfite, and some minor chemicals. The output data comprised the deinking pulp products, wastewater, and sludge. The deinking pulp flow diagram is shown in Fig. 3.

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Table 3: Life cycle impact assessment results of DB and FB paper products

Impact category	Unit	DB	FB	Impact assessment method
GWP-f	kg CO_2 eq	1.848	2.651	IPCC
ADP-f	MJ	14.668	22.396	CML
AP	kg SO_2 eq	8.12	13.95	CML
$PM_{2.5}$	kg $PM_{2.5}$ eq	2.12	3.27	ILCD 2011
HTC	CTUh	1.71E-06	2.07E-06	USEtox

steam and electricity, called co-generation. A generator set powered by diesel oil fuel and low-pressure steam from biogas is added to support energy needs. The biogas energy generator produces low-pressure steam from burning methane gas derived from anaerobic wastewater treatment. In addition, to using captive energy, factories use small amounts of electricity from the grid. The fossil fuel proportion of X factory for power generation is 96% comprising coal and fuel oil. The X factory is highly dependent on fossil fuels due to the limited source of renewable energy on the island where the factory is located.

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The interpretation of inventory contribution to impact results is shown in Figs. 6 and 7. The significant inventory process of GWP-f comes from coal burning for energy generation, relatively contributing 55% and 40% of the total GWP for DB and FB products, respectively, followed by electricity and calcium carbonate consumption. The impact of

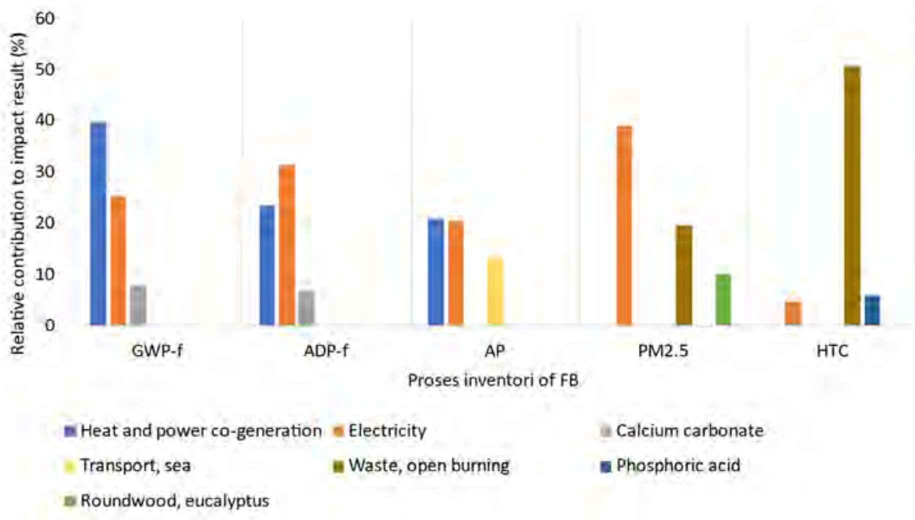

Fig. 6: Inventory contribution of FB product on life cycle impact result

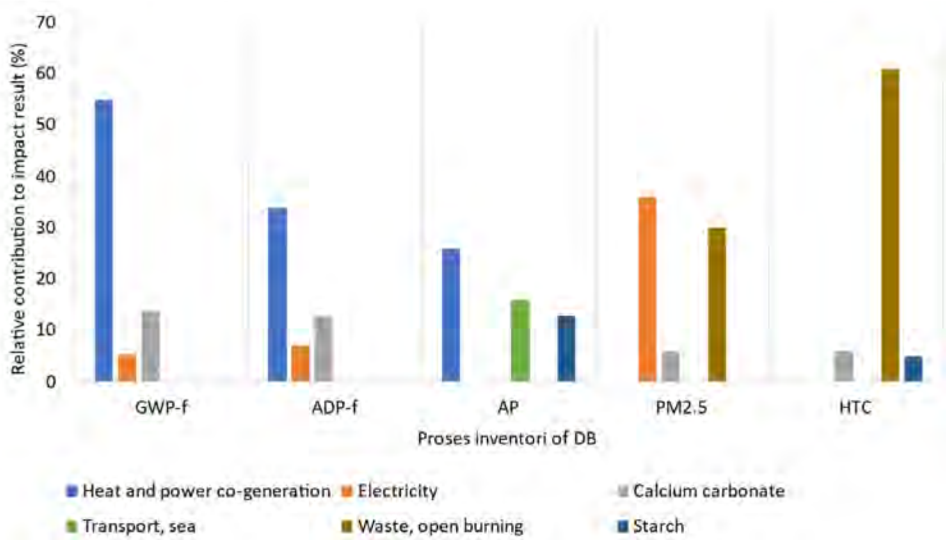

Fig. 7: Inventory contribution of DB product on life cycle impact result

coal combustion and electricity production on GWP has been demonstrated in previous research on pulp and paper making, showing that energy generation (steam and electricity) sourced from coal combustion is the main contributor to carbon footprint (Zhao *et al*., 2019). The most significant inventory process of DB products on the ADP-f impact comes from coal combustion, with a 34% relative contribution; meanwhile, electricity usage significantly contributes 31% to FB products. The most significant inventory process on the impact of $PM_{2.5}$ particulates comes from electricity use, relatively contributing 36% and 39% for DB and FB paper, respectively, followed by open burning of product disposal. Other studies have shown the impact of electricity and open burning on $PM_{2.5}$ emission; the increase in electricity consumption increases $PM_{2.5}$ emission in Singapore (You *et al*., 2017); industrial boilers contribute to higher $PM_{2.5}$ concentration in China (Zhang *et al*., 2018); smoke haze from burning activity of forest and agriculture impact to metal bound with $PM_{2.5}$ (Akbari *et al*., 2021). On the AP impact, the largest source inventory of FB products comes from coal combustion and electricity usage, with 21% and 20%, respectively. The largest source of DB product comes from coal combustion, relatively contributing 26%. The impact of coal combustion and electricity production on AP has also been demonstrated in previous studies; coal-fired plant contributes to acidification impact sourced from SO_2, NO, and NO_2 emission (Rewlay-ngoen *et al*., 2014). Electricity production is the main contributor to the acidification impact (Kameni Nematchoua, 2022). Open burning of product disposal was the largest contributor to the HTC impact, relatively contributing 61% and 51% for DB and FB paper, respectively. Open burning produces organic pollutants, such as polychlorinated biphenyls, polychlorinated dibenzo-p-dioxin (PCDD), polycyclic aromatic hydrocarbons (PAHs), and other substances. Other research has shown that biomass open burning contributes to higher concentrations of persistent organic pollutants (Chang *et al*., 2013). Open burning from municipal solid waste can bring high carcinogenic risks to human health due to PAHs (Cheng *et al*., 2022). Incense burning in China was highly correlated with the increase in PAHs concentration (Bootdee *et al*., 2018), and toxic heavy metals resulted from open burning of municipal solid waste in China (Wang *et al*., 2017).

A deep analysis of the stage's contribution shows that virgin pulp plays a more significant role in the impact result than deinking pulp. Virgin pulp contributes 41%, 49%, 46%, 35%, and 30% for the overall result of GWP-f, ADP-f, AP, $PM_{2.5}$, and HTC impact of FB product, while deinking pulp contributes at 8%, 7%, 8%, 5%, and 3% on the same impact of DB products, respectively. According to the inventory contribution analysis, the significant contribution for all impacts is sourced from energy generated from coal combustion and electricity use. The pulp production from virgin fiber is more complex than the deinking pulp production process. The energy required in the deinking pulp manufacturing process is 3 giga joules (GJ) per ton of pulp product. In comparison, the energy consumption for virgin pulp production is higher, with the pulp-1 factory requiring 16 GJ per ton of pulp product and the pulp-2 factory requiring 17 GJ per ton. The complex process requires more energy, causing a high all-parameter impact of FB compared to DB products. Research on pulp and paper production in China shows that energy consumption for virgin bleach kraft pulp, BCTMP pulp, and deinking pulp production was around 15 GJ, 13 GJ, and 6 GJ per ton pulp (Man *et al*., 2019), respectively. Meanwhile, in The Netherlands, the energy consumption of deinking pulp production was around 2.3–3.0 GJ per ton pulp (Laurijssen *et al*., 2013). The study also indicates that the main raw materials, specifically LBKP, NBKP, and BCTMP pulp, of FB production are slightly higher than that of DB production, which uses deinking pulp, NBKP, and BCTMP pulp. This material difference contributes to the higher overall environmental impact of FB products. The amount of pulp materials needed for making one ton of FB product is 0.8 tons, while for DB is 0.72 tons. The high amount of main raw materials used in FB production required high energy input throughout the production process. The life cycle interpretation analysis shows that energy generation from coal combustion contributes to most of the impact categories, with pulp and paper manufacture stages having high energy consumption. Energy and material consumption efficiency must increase the sustainability of pulp and paper production.

CONCLUSION

This study presents a comparative life cycle assessment of two comparable paper products: 1) a duplex board based on 93% recycled fiber and 2) a folding boxboard based on 100% virgin wood fiber with a cradle-to-grave system boundary. The life cycle inventory data for the production stage were based on pulp and paper factories operating in Indonesia, whereas the upstream (raw material acquisition) and downstream activities (distribution, use, and waste management) were modeled based on secondary data and assumptions. It was concluded that the duplex board is more environmentally preferable to the folding boxboard across all the impact categories assessed, including GWP fossil, acidification, particulates, abiotic depletion-fossil, and HTC. The contribution analysis further reveals that the energy input is the main contributor to the overall impact of both product systems. The results of the impact assessment of fossil GWP, acidification, particulates, fossil abiotic depletion, and human toxicity for the cancer category of duplex paper products were 1,848.26 kg CO_2 eq, 8.12 kg SO_2 eq, 2.12 $PM_{2.5}$ eq, 14,668.06 MJ, 1.7E-6 CTUh, while for folding boxboard products 2,651.25 kg CO_2 eq, 13.95 kg SO_2 eq, 3.27 kg $PM_{2.5}$ eq, 22,395.81 MJ and 2.1E-6 CTUh, respectively. All impact magnitudes were measured in functional units per 1 tonne of paper product. The pulp and paper production stage significantly contributes to GWP, ADP-f, $PM_{2.5}$, and AP impact on paper products from virgin fiber material, while the paper production stage contributes to the same impacts on paper from recycled fiber. Disposal stages significantly contribute to HTC's impact of HTC on both products. Coal combustion and electricity use are inventory processes mostly contributing to GWP, ADP-f, $PM_{2.5}$, and AP impacts, while open burning of disposal highly contributes to HTC impacts. The study highlights the greater process complexity and energy requirements in producing pulp from virgin fiber than deinking pulp production. This complexity contributes to the higher overall environmental impacts of paper products from virgin fiber material than recycled fiber material. The number of main raw materials used for folding boxboard production was also slightly higher than duplex board production, contributing to higher energy input required to produce the former is higher than that of the latter. Although LBKP pulp is produced by partially using a biomass-based fuel, the intensive use of energy in overall production makes it less preferred than the duplex board. Among other previous research on pulp and paper products, none of the research was conducted in Indonesia, mainly for complete life cycle stages from cradle to grave. This research is important to provide recommendations for pulp and paper stakeholders, particularly in Indonesia, in making policies and decisions regarding environmental-friendly paper products. This study presents the environmental impact of paper production based on virgin wood and recycled fiber material, showing the advantage of recycled fibers; however, the recycled fibers have quality limitations in cycle use. More studies must be applied to the combination of environmental and quality impact of both fibers.

AUTHOR CONTRIBUTIONS

J. Simamora contributed to the data collection and observation, life cycle assessment, manuscript preparation, and revision. M. Yani, the corresponding author, supervised the life cycle assessment and proofread the manuscript. E.I. Wiloso supervised the data collection, scope determination, and impact analysis.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
ADP-f	Abiotic depletion potential – fossil
AoX	Adsorbable Organic Halides

AP	Acidification potential
BCTMP	Bleached Chemi-Thermomechanical Pulp
BOD	Biochemical oxygen demand
CML	Centre for Environmental Studies
CO_2	Carbon dioxide
$CO_2 eq$	Carbon dioxide equivalent
COD	Chemical oxygen demand
CH_4	Methane
CTUh	Comparative Toxic Unit for human
DB	Duplex board
EPD	Environmental product declaration
Eq	Equivalent
FB	Folding boxboard
GHG	Greenhouse gas
GJ	Giga Joule
GWP	Global warming potential
GWP-f	Global warming potential – fossil
H_2S	Hydrogen sulfide
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
HTC	Human toxicity – cancer
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
Kg	Kilogram
Km	Kilometer
KWh	Kilowatt-hour
LBKP	Leaf Bleached Kraft Pulp
LCA	Life cycle assessment
MJ	Mega Joule
NBKP	Needle Bleach Kraft Pulp
NO_2	Nitrogen dioxide
MFO	Marine fuel oil
OMG	Old magazines
ONP	Old newspaper
PAHs	Polycyclic aromatic hydrocarbons
PCBs	Polychlorinated biphenyls
PCDD	Polychlorinated dibenzo-p-dioxin
PEFCR	Product Product Environmental Footprint Category Rules
PM	Particulate matter
$PM_{2.5}$	Fine particulate matter
$PM_{2.5} eq$	Fine Particulate matter
PM_{10}	Particulat matter with particles sice below 10 micrometer
$PM_{>10}$	Particulat matter with particles sice above 10 micrometer
RAINS	Regional Air Pollution Information and Simulation
SIPSN	National Waste Management Information System
SNI	Indonesian National Standard
SO_2	Sulfur dioxide
$SO_2 eq$	Sulfur dioxide equivalent
SOP	Shorted office paper
SWL	Shorted white ledger
Ton.km	Ton.kilometer
TSS	Total suspended solid
USEtox	United Nations Environment Program-Society for Environmental Toxicology and Chemistry toxicity model
WBCD	World Business Council for Sustainable Development
WRI	World Resources Institute

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Podcasts

SPECIAL ISSUE: Eco-friendly sustainable management
CASE STUDY

Sustainable healthy settlement on a small island as a cultural heritage area

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ABSTRACT

BACKGROUND AND OBJECTIVES: Penyengat Island is a small island in the Riau Archipelago Province, Indonesia, with a coastal settlement that embodies traditional Malay values. This island holds significance due to the historical connection to the Malay royal civilization along the Malacca Strait, which includes Indonesia, Malaysia, and Singapore. Therefore, this research analyzes the status and determinants of the sustainability of healthy settlement arrangements in the coastal area of Penyengat Island as a cultural heritage site.
METHODS: The study utilizes the multi-dimensional scaling-rapid appraisal for sustainability approach, employing the modified rapid appraisal for fisheries ordinance software technique for settlement analysis. Data collection was performed using a survey and literature review. The survey was conducted through field observations and interviews with respondents, while a literature review was carried out through secondary data collection related to settlements and cultural heritage. The data analysis was performed using multi-dimensional scaling, modified from the rapid assessment appraisal method for fisheries.
FINDINGS: The study reveals that the sustainability index status for the ecological and institutional legal dimensions in Penyengat island is sustainable. In contrast, the economic and socio-cultural dimensions recorded low sustainability, while the green infrastructure dimension was deemed unsustainable. Several attributes significantly influenced the sustainability of healthy settlement arrangements in the coastal area of Penyengat Island, including household waste management, lighting in houses, noise levels, residential density, clean water supply, corporate social responsibility (CSR) funding, occupation, income growth, technological innovation, tourist numbers, public perception of the distance between cultural heritage and settlements, social conflicts, implementation of mutual cooperation, community group management, handling cross-program problems, education and training, settlement regulations, community organization regarding settlements, socialization of regulations, cultural heritage organizations, hedgerows, additional vegetation, tree canopy expansion, and rain gardens. The multi-dimensional scaling analysis indicated that the ecological dimension of sustainability ranged from 51.71 to 60.67, corresponding to the moderate status in *Rukun Warga* 1 to 5. The economic dimension ranges from 40.46 to 48.23, indicating a less advanced status in *Rukun Warga* 1 to 5. The socio-cultural dimension ranges from 48.97 to 51.78, representing sufficient status in *Rukun Warga* 1 and less sustainable in *Rukun Warga* 2 to 5. The institutional, legal dimension ranges from 50.18 to 71.24, with a sufficiently continuous status in *Rukun Warga* 1 to 5. Lastly, the green infrastructure dimension ranges from -0.12 to 6.72, a non-continuous status in *Rukun Warga* 1 to 5.
CONCLUSION: The sustainability status of healthy settlement arrangements on Penyengat Island is relatively good. While Penyengat Island has made significant strides in achieving sustainable settlement arrangements, the green infrastructure dimension requires attention. Enhancing sustainability in this dimension involves addressing socio-cultural aspects and improving the institutional and legal framework. In summary, Penyengat Island can progress toward a more sustainable and resilient future by fostering community involvement, strengthening governance structures, and implementing sustainable practices.

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INTRODUCTION

Penyengat Island is a small island with an area of 4 km^2 in the Riau Archipelago Province, Indonesia (CBS, 2021). This location has been proposed as a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Site due to the numerous cultural heritage buildings related to the Malay kingdom in the Straits of Malacca and is surrounded by coastal settlements. As the local population continues to grow, there is a need for more residential land, resulting in the construction of housing areas on the remains of cultural heritage buildings (Rijal *et al.,* 2019). An earlier study has identified several issues on Penyengat Island, including domestic waste management, tourism activities and clean water deficiency (Rosdatina *et al.,* 2019). Preserving existing reserve sites also requires better maintenance and support from the government, private sectors, and the community. Furthermore, health problems such as upper respiratory tract infection and tuberculosis require attention from the government to achieve Indonesia's national target of eliminating tuberculosis by 2035 and obtaining a tuberculosis-free status by 2050 (Martias and Dhermawan, 2018). Failure to organize the settlement on Penyengat Island could lead to environmental problems, which pose a risk to public health and deter foreign tourists from visiting the island. An integrated and comprehensive approach is essential in addressing the issues related to human settlements and the preservation of cultural heritage sites. The concept of healthy settlements and housing should incorporate sociological and technical considerations, including risk factor management, location, building design, qualifications, adaptation, management, use, maintenance, drinking water supply, adequate facilities for cooking, washing, food storage, and proper waste disposal (Ramelan *et al.,* 2017). The sustainable management of coastal settlements could be achieved through environmental rejuvenation, renovation and resettlement programs. Community empowerment and adequate funding would create a self-reliant society capable of handling settlement problems in coastal areas (Surya *et al.,* 2020). Thus, the current study aims to analyze the status and determinants of healthy settlement arrangements on Penyengat Island, particularly in the cultural heritage area, to enhance public health. This novel study discussed the physical (ecological dimensions and green infrastructure) and non-physical aspects (economic, socio-cultural, and institutional legal dimensions) based on the research findings and addressed the related issues accordingly. This study was conducted on Penyengat Island, Tanjungpinang City, Riau Archipelago Province, Indonesia, in 2022.

MATERIALS AND METHODS

Methods

This research utilized primary and secondary data. The primary data consisted of field observations and interviews with the residents. A checklist of standard parameters was developed by the researchers for the field observation. Meanwhile, interviews with the residents of Penyengat Island were conducted using a closed-ended questionnaire. Subsequently, the researchers sorted the interview findings and observation sheets according to previous studies with minor modifications. The secondary data was obtained from statistical sources (demographic, environmental, economic (RMPWPH, 2006), and socio-cultural data) and processed data from relevant agencies and previous research conducted on Penyengat Island (DMHRI, 1999). The sample size was determined using total sampling with inclusion and exclusion criteria. Respondents were recruited using proportional random sampling, as outlined in Table 1. In addition, the dimensions of healthy settlement arrangement on Penyengat Island comprise five dimensions and 50 attributes (see Table 2).

Table 1. Total Population and sample in the administrative region of Penyengat Island

No.	Location	Total Population/ Family Card	Number sample/ Family Card
1	RW1	204	79
2	RW2	129	63
3	RW3	160	43
4	RW4	136	68
5	RW5	151	64
Total		780	317

Table 2. Dimensions and attributes of sustainable settlement arrangement in the coastal area of Penyengat Island as a cultural heritage site

Attributes	Dimension
(1) Location; (2) Infrastructure; (3) Disease vectors; (4) Provision of clean water; (5) Household waste; (6) Garbage; (7) Occupancy density; (8) Indoor lighting; (9) Noise; (10) Building density; (11) Vegetation density.	*Ecology* (DMHRI, 1999)
(1) Community income; (2) Increase in income; (3) Decrease in income; (4) Number of tourists; (5) Type of work; (6) Job opportunities; (7) Corporate social responsibility funding support; (8) Market potential; (9) Dependence on tourism activities to support the economy; (10) Technological innovation that supports the people's economy.	*Economy* (RMPWPH, 2006)
(1) Community involvement in social activities; (2) Community group management; (3) Implementation of mutual cooperation; (4) Community knowledge level; (5) Local wisdom; (6) Public health degree; (7) Community perceptions about the distance between cultural heritage and settlement; (8) Community perception of housing conditions; (9) Community perceptions about the condition of cultural heritage; (10) Social conflict; (11) Government efforts to reallocate settlements.	*Social* (Butar-butar and Soemarno, 2012)
(1) Government apparatus dealing with settlement issues; (2) Government apparatus dealing with cultural heritage issues; (3) Community organizations dealing with settlement issues; (4) Community organizations dealing with cultural heritage issues; (5) Education and training for government officials; (6) The handling of health problems in settlements and cultural heritage is carried out through cross-programs; (7) Cultural conservation area regulations; (8) Healthy settlement arrangement regulations; (9) Dissemination of regulations regarding cultural heritage and settlement arrangements.	*Legal and Institutional* (Ariwibowo *et al.,* 2022)
(1) Addition of vegetation; (2) Rain gardens; (3) green roofs; (4) Rain barrels (5) Permeable pavements ; (6) Green walls ; (7) Xeriscaping; (8) Hedgerows; (9) Tree Canopy Expansion.	*Green Infrastructure* (Grum and Grum, 2020)

The sustainability analysis of healthy settlements was conducted using the multi-dimensional scaling (MDS) approach with the modified Rapfish software, Rapid Appraisal for Settlement Ecosystem (Rapsettle) (Kavanagh and Pitcher, 2004). The sustainability index was determined based on a scale of 0 (bad) to 100 (good) with the following outcomes: 00.00 - 20.00 (bad/unsustainable), 20.01 - 50.00 (less sustainable), 50.01-75.00 (quite sustainable), and 75.01-100.00 (good/sustainable). The leverage analysis was employed to identify the influential factors, while the Monte Carlo analysis assessed the impact of scoring errors for each attribute (Azizah *et al.,* 2023).

Analysis of existing conditions and ecological dimensions

The selection criteria (not available, optimal, and less optimal) were adopted from previous research. For instance, attributes such as community involvement in social activities are considered in the socio-cultural dimension, modified from Blind and Sumarno (2012).

(0) None: No CSR funding

(1) Less Optimal: The CSR funding is available but does not meet the target

(2) Optimal: The CSR funding support is available and utilized optimally and on target

These benchmarks were adopted and modified from Tesfamichael and Pitcher, 2006.

Study area

The geographic location of the study area is Penyengat Island, Tanjungpinang City, Riau Archipelago Province, Indonesia, in 2022 (see Fig. 1).

RESULTS AND DISCUSSION

Environmental condition on Penyengat Island

Penyengat Island is characterized by a dense coastal township with residential areas near cultural heritage buildings. The island topography consists primarily of coastal lowlands with several hilly areas. The average temperature on Penyengat Island is 27.4 degrees Celsius (°C), with a humidity level of approximately 83 per cent (%) and an average daily rainfall of 188.1 mm (TCRR, 2018). The island is home to 46 cultural heritage sites scattered across different locations (Pristiwasa and Augustinus, 2017). Penyengat Island is primarily accessed via water transportation, such as motorized boats (pompongs) and non-motorized boats, as there are limited land transportation options consisting of two-wheeled and three-wheeled vehicles (motorized rickshaws) (Destiana *et al.,* 2020). Education facilities on the island are limited to Junior High School (SMP) level,

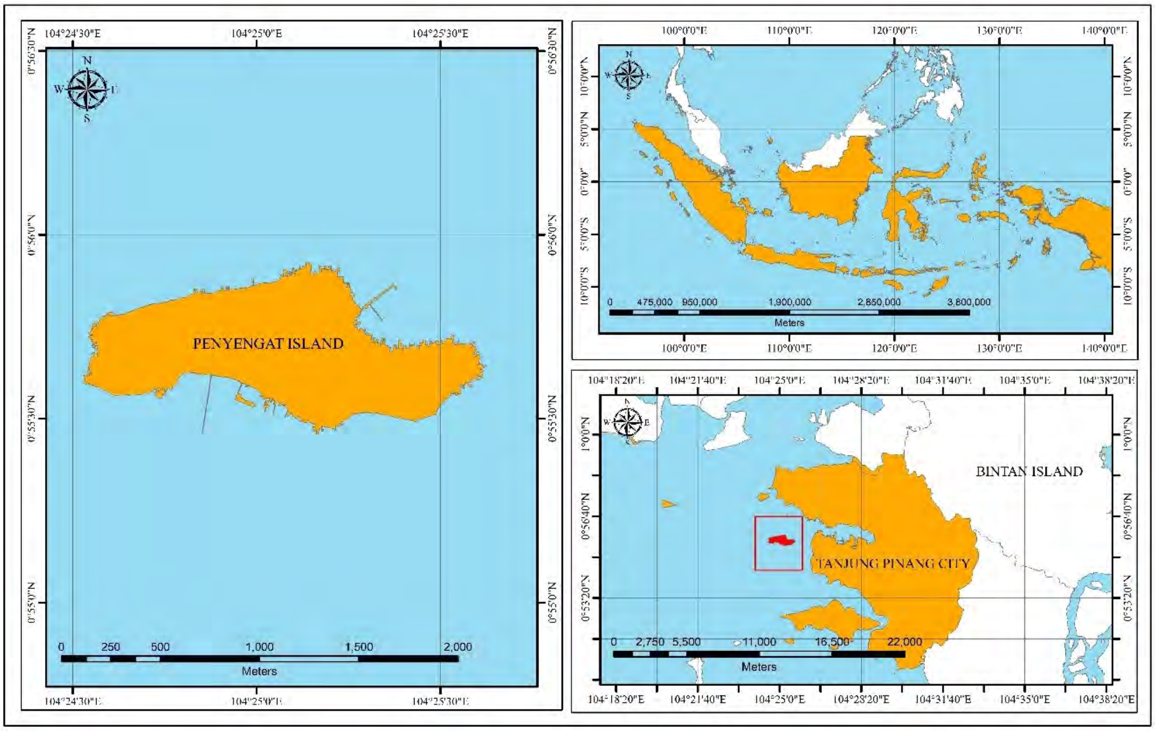

Fig. 1: Geographic location of the study area in Penyengat Island, Indonesia

and students who wish to pursue higher education are required to travel to Tanjungpinang City. Similarly, healthcare facilities on Penyengat Island are limited to auxiliary health centers, private midwives, and posyandu practices being the primary healthcare providers. Thus, residents are forced to seek medical assistance at hospitals in Tanjungpinang City during emergencies. The economy of Penyengat Island is supported by local shops and stalls, catering to the needs of residents and tourists (Mahadiansar and Romadhon, 2021).

Analysis of existing conditions and ecological dimensions on Penyengat Island

Analysis of the ecological conditions of settlements on Penyengat Island was performed according to the standards stipulated by the Ministry of Health, Decree Number. 829 of 1999 concerning Housing Health Requirements (DMHRI, 1999). The parameters evaluated in this study include location, infrastructure, disease vectors, clean water, household waste, garbage, residential density, lighting, noise, and building and vegetation density(Table 3). The health quality situation in housing is the most crucial factor for housing sustainability (Nasrabadi and Hataminejad, 2019).

The condition of the drainage waste network in RW1, RW2, RW4, and RW5 did not meet the standard requirements. Settlements on the coast often dispose of domestic wastes directly into the sea, leading to water pollution. Wastewater on Penyengat island includes domestic wastewater used for bathing and washing (gray water) and concentrated waste (black water) from households and other public and social facilities. Waste management that does not comply with local and international standards negatively impacts the environment, public health and society (Sunarti *et al.,* 2021; Asteria and Haryanto, 2021; Brotosusilo *et al.,* 2022; Elsaid and Aghezzaf, 2023). Poor housing quality has also been associated with numerous health conditions, including cognitive delays among children from neurotoxin exposure (Hernandez, 2019). Environmental protection should be prioritized when implementing the principles

Table 3: Analysis of existing settlements conditions in terms of ecological dimensions on Penyengat Island

No.	Ecology attribute		Criteria	RW1	RW2	RW3	RW4	RW5
1	Location	(0) (1) (2)	Not eligible Less qualified Qualify	(1)	(1)	(1)	(1)	(1)
2	Infrastructure	(0) (1) (2)	Not eligible Less qualified Qualify	(1)	(1)	(1)	(1)	(1)
3	Disease vectors	(0) (1) (2)	Not eligible Less qualified Qualify	(1)	(1)	(1)	(1)	(1)
4	Provision of clean water	(0) (1) (2)	Not eligible Less qualified Qualify	(1)	(2)	(2)	(1)	(2)
5	Household waste	(0) (1) (2)	Not eligible Less qualified Qualify	(0)	(0)	(1)	(0)	(0)
6	Garbage	(0) (1) (2)	Not eligible Less qualified Qualify	(1)	(1)	(1)	(1)	(1)
7	Occupancy density	(0) (1) (2)	Not eligible Less qualified Qualify	(2)	(1)	(1)	(1)	(2)
8	Indoor lighting	(0) (1) (2)	Not eligible Less qualified Qualify	(2)	(2)	(2)	(2)	(2)
9	Noise	(0) (1) (2)	Not eligible Less qualified Qualify	(2)	(2)	(2)	(2)	(2)
10	Building density	(0) (1) (2)	Tight Currently Not tight	(1)	(1)	(0)	(1)	(1)
11	Vegetation density	(0) (1) (2)	No vegetation Low vegetation Hight vegetation	(1)	(1)	(1)	(1)	(1)

of sustainable development and minimizing solid, liquid, and gas waste (Ghazali *et al.,* 2021; Zaman *et al.,* 2021; Weekes *et al.,* 2021; Alzghoul *et al.,* 2022; Le Dinh *et al.,* 2022). One of the recommendations to maintain and improve the quality of life that is in harmony with the environment is establishing “greening areas” (Gustiarini *et al.,* 2023).

Analysis of existing conditions and economic dimension on Penyengat Island

The economic dimension consists of 10 attributes that influence the sustainability of healthy settlement arrangements on Penyengat Island (see Table 4). Corporate social responsibility (CSR) funding is inadequate in supporting the island community. Local tourists predominantly drive tourism, necessitating robust marketing to promote Penyengat Island internationally. Given that Penyengat Island has been proposed as a world heritage site by UNESCO, CSR support is crucial for future development on the island. Furthermore, technological innovation that could enhance the local economy remains lacking. The local economy is mainly driven through a participatory approach by the community in all aspects and potential for development. This approach encourages creativity and self-reliance among the residents (Dewi, 2018). Another country that faces a similar vulnerability

Table 4: Analysis of existing settlement conditions in terms of economic dimension on Penyengat Island

No.	Economic attribute	Criteria	RW1	RW2	RW3	RW4	RW5
1	Community income	(0) Low (1) High (2) Very High	(1)	(1)	(1)	(1)	(1)
2	Income growth	(0) Low (1) High (2) Very High	(0)	(1)	(0)	(0)	(0)
3	Decreased income	(0) Low (1) High (2) Very High	(1)	(1)	(1)	(1)	(1)
4	Number of tourists	(0) Low (1) High (2) Very High	(1)	(1)	(1)	(1)	(1)
5	Type of work	(0) Low (1) High (2) Very High	(0)	(1)	(1)	(2)	(1)
6	Job opportunities	(0) Not available (1) Not fixed (2) Fixed	(1)	(1)	(1)	(1)	(1)
7	CSR funding	(0) Not available (1) Less than optimal (2) Optimal	(0)	(0)	(0)	(0)	(0)
8	Market potential	(0) Local (1) Local, national (2) Local, national, international	(1)	(1)	(1)	(1)	(1)
9	Dependence on tourism activities to support the economy	(0) Independent (1) Dependent (2) Highly dependent	(1)	(1)	(1)	(1)	(1)
10	Technological innovation to boost the people's economy	(0) Not available (0) Less than optimal (1) Optimal	(1)	(0)	(0)	(1)	(0)

in coastal areas is Jamaica, where the limited financial and technical resources and regulations by the central and regional governments led to poor economic growth and development (Ishemo, 2009).

Analysis of existing settlement conditions in terms of socio-cultural dimensions on Penyengat Island

The findings for each attribute in the socio-cultural dimension highlight the urgency for stronger support from the community and government in managing settlements and preserving cultural heritage (see Table 5). The residents opined that the government has not fully committed to effectively relocating settlements for residents who occupy former cultural heritage areas, leading to social conflicts due to land ownership disputes (Swastiwi, 2022). Therefore, providing, developing, and maintaining tourism facilities is essential to enhance the appeal of Penyengat Island's natural and historical assets while preserving the cultural identity (Jacom *et al.*, 2021). Empowering various community groups, engaging youth organizations with specific interests, and involving community leaders in tourism management is vital in promoting international tourism and ensuring effective island management (Arifin *et al.*, 2021). Moreover, improving public awareness in coastal areas will help the community to reduce associated risks and capitalizing on the opportunities related to climate change (Shaffril *et al.*, 2015). Most importantly, it is important to preserve and optimize the utilization of cultural resources, which are determining factors affecting ecotourism performance (Mulyadi, 2018).

Table 5: Analysis of the existing settlement's conditions in terms of socio-cultural dimensions on Penyengat Island

No.	Socio-cultural attributes		Criteria	RW1	RW2	RW3	RW4	RW5
1	Community involvement in social activities	(0) (1) (2)	Not available Less than optimal Optimal	(1)	(1)	(1)	(1)	(1)
2	Management of community groups	(0) (1) (2)	not available Less than optimal Optimal	(1)	(1)	(1)	(1)	(1)
3	Collaborative implementation	(0) (1) (2)	Not available Less than optimal Optimal	(1)	(1)	(1)	(1)	(1)
4	Community knowledge level	(0) (1) (2)	Lacking Enough Excellent	(1)	(1)	(1)	(1)	(1)
5	Local wisdom	(0) (1) (2)	Not available Less conserved Preserved	(1)	(1)	(1)	(1)	(1)
6	Public health degree	(0) (1) (2)	Lacking Enough Excellent	(1)	(1)	(1)	(1)	(1)
7	Community perceptions about the distance between cultural heritage and settlements	(0) (1) (2)	Very Close Near Far	(2)	(1)	(1)	(1)	(1)
8	Community perceptions of housing conditions	(0) (1) (2)	Not good Good Very good	(1)	(1)	(1)	(1)	(1)
9	Community perceptions about the condition of cultural heritage	(0) (1) (2)	Not good Good Very good	(1)	(1)	(1)	(1)	(1)
10	Social conflict	(0) (1) (2)	Very often Often Sometimes	(0)	(0)	(0)	(0)	(0)
11	Government efforts to relocate settlements	(0) (1) (2)	Not available Less than optimal Optimal	(1)	(1)	(1)	(1)	(1)

Analysis of existing settlements conditions in terms of institutional and legal dimensions on Penyengat Island

Regulations pertaining to cultural heritage areas and settlement arrangements are in place but incomplete and not effectively implemented. Government agencies responsible for the settlement and cultural heritage issues on Penyengat Island are perceived to be less than optimal in their approach (Sutianto *et al.,* 2023). The handling of housing health problems and cultural heritage preservation lacks an integrated and cross-program approach essential for supporting the sustainability of settlement arrangements on Penyengat Island (see Table 6). Establishing regional regulations to ensure legal certainty and active community involvement is essential in managing coastal areas, which aligns with the local community's wisdom and values. Formulating regional regulations encouraging community participation in coastal area management empowers coastal communities and promotes independent management (Ikhwan *et al.,* 2020). In addition, coastal zone planning and law enforcement are vital in managing coastal areas (Liu and Xing, 2019).

Analysis of existing settlements conditions in terms of green infrastructure dimensions on Penyengat Island

The state of attributes related to the green infrastructure dimension varied in this study (see

Table 6: Analysis of existing legal and institutional conditions on Penyengat Island

No.	Legal and institutional attributes	Criteria		RW1	RW2	RW3	RW4	RW5
1	Government approach in dealing with settlement issues	(0) (1) (2)	Not available Less than optimal Optimal	(1)	(2)	(1)	(1)	(1)
2	Government approach in dealing with cultural heritage issues	(0) (1) (2)	Not available Less than optimal Optimal	(1)	(2)	(1)	(1)	(1)
3	Community organizations approach to dealing with settlement issues	(0) (1) (2)	Not available Less than optimal Optimal	(1)	(2)	(1)	(1)	(1)
4	Community organizations approach to dealing with cultural heritage issues	(0) (1) (2)	Not available Less than optimal Optimal	(1)	(2)	(1)	(1)	(1)
5	Education and training for government officials	(0) (1) (2)	Not available Less than optimal Optimal	(1)	(1)	(1)	(1)	(1)
6	Handling of health problems in settlements and cultural heritage is carried out through cross-programs	(0) (1) (2)	Not available Less than optimal Optimal	(1)	(1)	(1)	(1)	(1)
7	Cultural conservation area regulation	(0) (1) (2)	Not available Incomplete Complete	(1)	(2)	(1)	(1)	(1)
8	Healthy settlement arrangement regulations	(0) (1) (2)	Not available Incomplete Complete	(1)	(1)	(1)	(1)	(1)
9	Dissemination of regulations regarding cultural heritage and settlement arrangements	(0) (1) (2)	Not available Less than optimal Optimal	(1)	(1)	(1)	(1)	(1)

Table 7). Adding vegetation and natural features to improve air quality in RW4 meets the qualified condition (2). In contrast, the hedgerow, which serves as a wind buffer and wildlife habitat in RW2 and RW3, was in less than qualified condition (1). Therefore, there is an urgent need to address the criteria that do not meet the requirements to improve the green infrastructure dimensions on the island. Renovation of residential buildings that are not in accordance with standards should also be avoided, as this step could increase energy consumption (Gabel *et al.*, 2023).

Sustainability index

The Rapsettle analysis was conducted in five locations (five RW) on Penyengat Island, which was determined based on the division of administrative areas. Table 8 details the sustainability index values for each dimension, stress values and R^2.

Table 8 demonstrates the differences between findings in the MDS and the small Monte Carlo analysis. The small Monte Carlo analysis indicated that the scoring errors are relatively small, with minimal variation in scoring due to differences in opinion, stable analysis process, and the occurrence of data entry errors or lost data was avoided. These results indicated that the MDS analysis used is valid and reliable for assessing the sustainability of healthy settlement arrangements on Penyengat Island. The validity of the MDS analysis results can also be assessed by examining the Goodness of Fit values, specifically the stress value and the coefficient of determination (R^2) at the 95% confidence level. Table 6 demonstrates that the stress value < 0.25 and the R^2 value is close to 1, suggesting that the analysis results are statistically valid and that there is no need for additional attributes as the analyzed aspects accurately reflect the actual conditions. These attributes effectively explained the sustainability of healthy settlements, and the results provided strong evidence that the Rapsettle analysis for determining the sustainability

Table 7: Analysis of the settlements existing conditions in terms of green infrastructure on Penyengat Island

No.	Atribut		Criteria	RW1	RW2	RW3	RW4	RW5
1	Addition of vegetation	(0) (1) (2)	Not eligible Less qualified Qualified	(0)	(0)	(0)	(2)	(0)
2	Rain gardens	(0) (1) (2)	Not eligible Less qualified Qualified	(0)	(0)	(0)	(0)	(0)
3	Green roof	(0) (1) (2)	Not eligible Less qualified Qualified	(0)	(0)	(0)	(0)	(0)
4	Rain barrels	(0) (1) (2)	Not eligible Less qualified Qualified	(0)	(0)	(0)	(0)	(0)
5	Permeable pavements	(0) (1) (2)	Not eligible Less qualified Qualified	(0)	(0)	(0)	(0)	(0)
6	Green walls	(0) (1) (2)	Not eligible Less qualified Qualified	(0)	(0)	(0)	(0)	(0)
7	Xeriscaping	(0) (1) (2)	Not eligible Less qualified Qualified	(0)	(0)	(0)	(0)	(0)
8	Hedgerow	(0) (1) (2)	Not eligible Less qualified Qualified	(0)	(1)	(1)	(0)	(0)
9	Tree canopy expansion	(0) (1) (2)	Not eligible Less qualified Qualified	(0)	(0)	(0)	(0)	(0)

of settlement arrangements around the Penyengat Island cultural heritage area is highly reliable. The ecological dimension sustainability status was analyzed using MDS analysis, which categorized the sustainability status. The MDS analysis of the ecological dimension attributes revealed the index value and sustainability status in the sufficiently sustainable category for all locations (RW1, RW2, RW3, RW4, and RW5). The sustainability index values in RW1 - RW5 ranged from 51.71 (lowest in RW4) to 60.37 (highest in RW5), indicating a fairly sustainable category (see Fig. 2).

The leverage analysis revealed five attributes that act as levers for the sustainability of the ecological dimension: 1) household waste, 2) lighting in the house, 3) noise, 4) occupancy density, and 5) clean water supply (see Fig. 3). A research conducted in India concerning industrial and household waste disposal reported a decline in water quality in coastal areas and watersheds (Krishnakumar *et al.,* 2017).

The MDS analysis for the attributes in the economic dimension indicated that the index value and sustainability status are in the less sustainable category for all locations (RW1, RW2, RW3, RW4 and RW5). The highest index value is in RW4 (48.23), with a less advanced status (see Fig. 4).

The leverage analysis conducted on the economic dimension identified five attributes as sustainability levers: (1) CSR support, (2) Type of work, (3) Income growth, (4) Technological innovation, and (5) Number of tourists (see Fig. 5). Support from various stakeholders, including the government and private sectors, is crucial in enhancing the economic potential of Penyengat Island. Contribution from the private sector through CSR funding could significantly improve the local economy on Penyengat Island (Prayuda *et al.,* 2022). Furthermore, boosting tourism in the archipelago would create job opportunities for local residents (Francis and Nair., 2020).

The MDS analysis of the attributes for the socio-cultural dimension demonstrates the index value and sustainability status for RW1 was sufficiently

Table 8. The MDS, Monte Carlo, sustainability status and statistics analysis

No.	Dimensions	MDS	Monte Carlo	Difference	Sustainability Status	Stress	R^2
1	*Ecology*					0.16	0.95
	RW1	55.77	55.36	0.41	quite sustainable quite sustainable		
	RW2	55.32	55.04	0.28	quite sustainable quite		
	RW3	57.03	56.30	0.73	sustainable quite sustainable		
	RW4	51.71	51.60	0.11			
	RW5	60.37	59.52	0.85			
2	*Economy*					0.17	0.94
	RW1	40.46	40.70	0.24	less sustainable		
	RW2	45.85	45.95	0.1	less sustainable		
	RW3	43.33	43.68	0.35	less sustainable		
	RW4	48.23	48.57	0.34	less sustainable		
	RW5	43.33	43.70	0.37	less sustainable		
3	*Socio-cultural*					0.19	0.92
	RW1	51.78	51.59	0.19	quite sustainable		
	RW2	48.97	49.19	0.22	less sustainable		
	RW3	48.97	48.70	0.27	less sustainable		
	RW4	48.97	49.13	0.16	less sustainable		
	RW5	48.97	49.04	0.07	less sustainable		
4	*Law and Institutions*					0.21	0.92
	RW1	50.18	50.32	0.14	quite sustainable quite		
	RW2	71.24	69.65	1.59	sustainable		
	RW3	50.18	50.16	0.02	quite sustainable quite		
	RW4	50.22	50.26	0.04	sustainable		
	RW5	50.22	50.07	0.15	quite sustainable		
5	*Green Infrastructure*					0.13	0.95
	RW1	-0.12	2.91	3.03	unsustainable		
	RW2	6.71	9.63	2.92	unsustainable		
	RW3	6.72	8.83	2.11	unsustainable		
	RW4	3.92	7.15	3.23	unsustainable		
	RW5	-0.12	3.36	3.48	unsustainable		

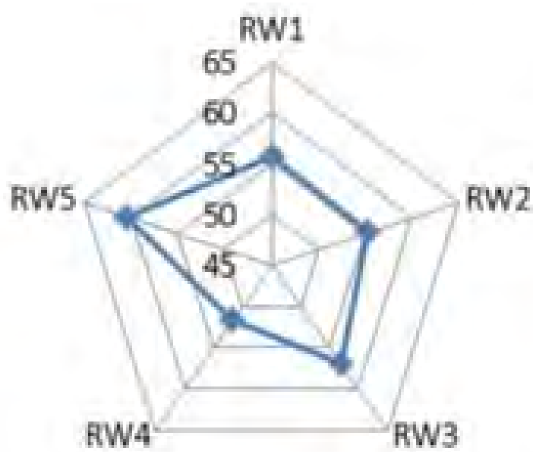

Fig. 2: Kite diagram of the ecological dimension showing the score for the sustainability status of settlement planning on Penyengat Island

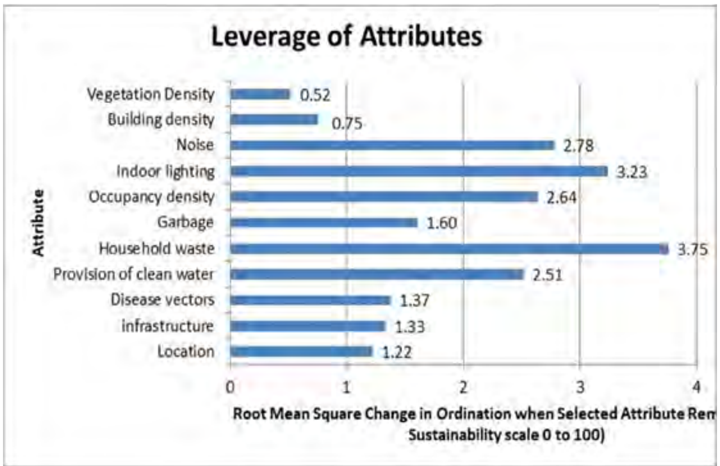

Fig. 3: Leverage attributes of the ecological dimension

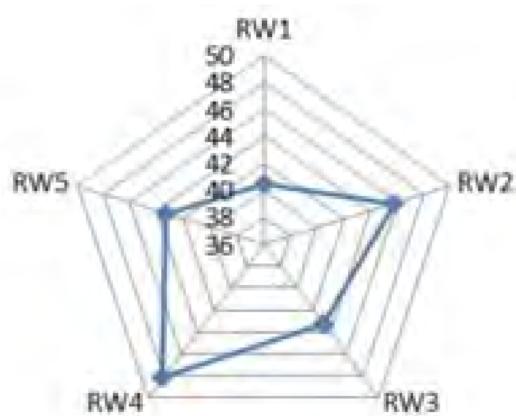

Fig. 4: Kite diagram of the economic dimension demonstrating the score for the status of the sustainability of settlement planning on Penyengat Island

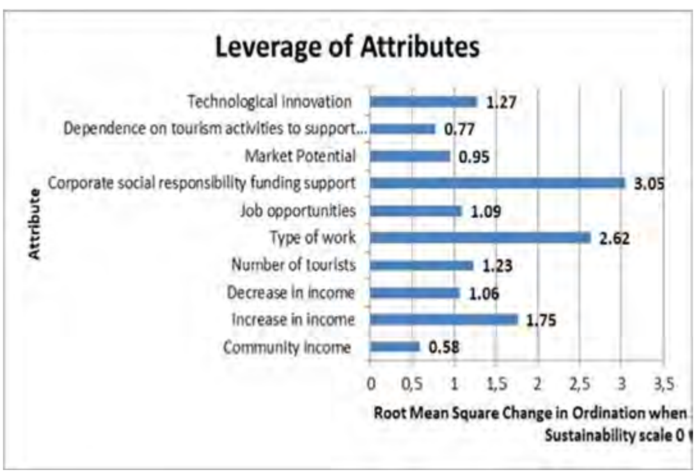

Fig. 5: Sustainability attribute leverage in the economic dimensions

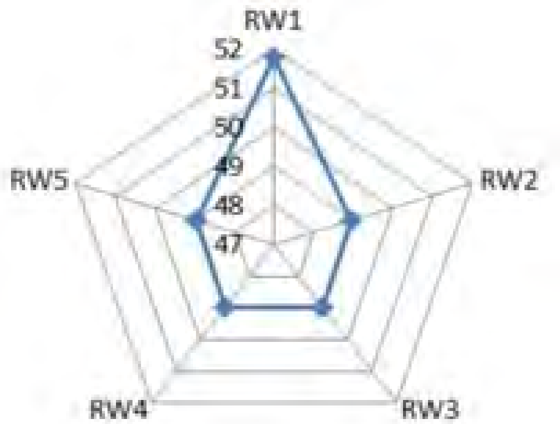

Fig. 6: Kite diagram of the socio-cultural dimension showing the score for the status of the sustainability of settlement planning on Penyengat Island

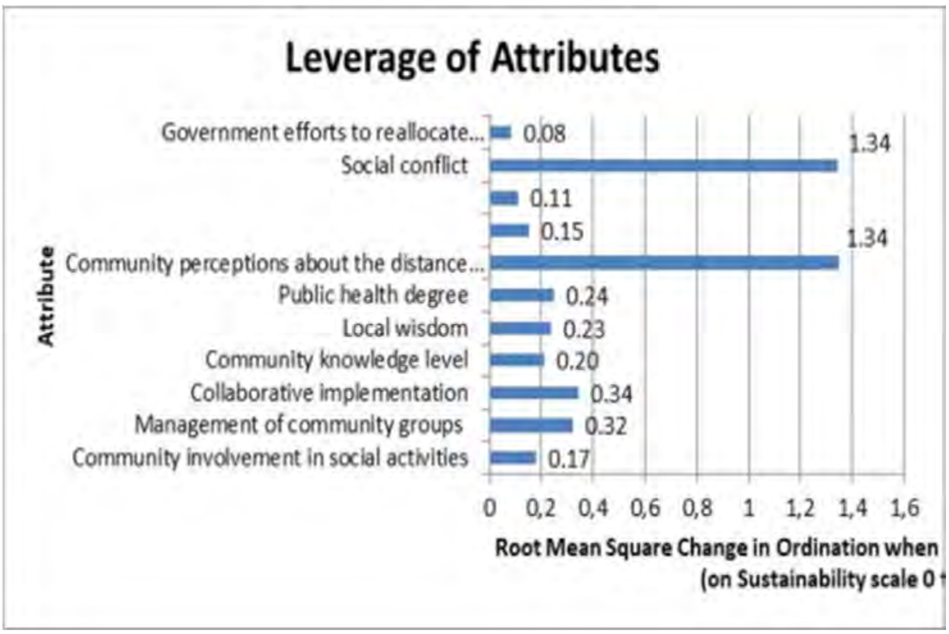

Fig. 7: Sustainability attribute leverage for socio-cultural dimensions

continuous, while RW2, RW3, RW4 and RW5 were categorized as less continuous. The highest index value was recorded in RW1 (51.78) with a sufficiently continuing status (see Fig. 6).

The leverage analysis conducted on the socio-cultural dimension identified four attributes as sustainability levers: (1) Community perceptions about the distance between cultural heritage and settlements, (2) Social conflict, (3) Implementation of mutual cooperation, and (4) Management of community groups (see Fig. 7). It is essential to focus on improving the quality of human resources to enhance social development on Penyengat Island. The community expects the authority to focus on five main sectors, namely infrastructure, health, culture, social, and environment, in implementing

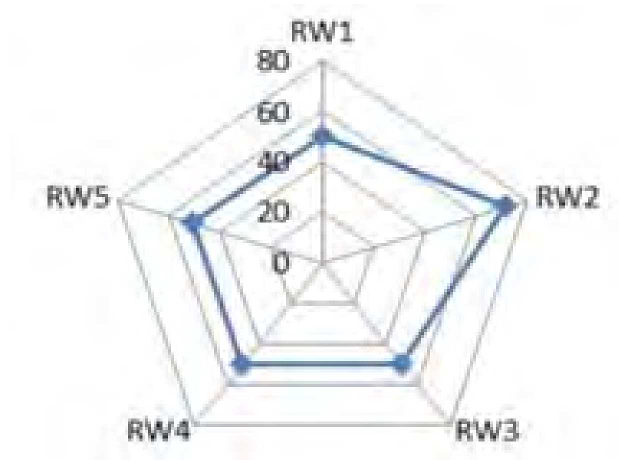

Fig. 8: Kite diagram of institutional legal dimensions showing the score for the sustainability status of settlement arrangements on Penyengat Island

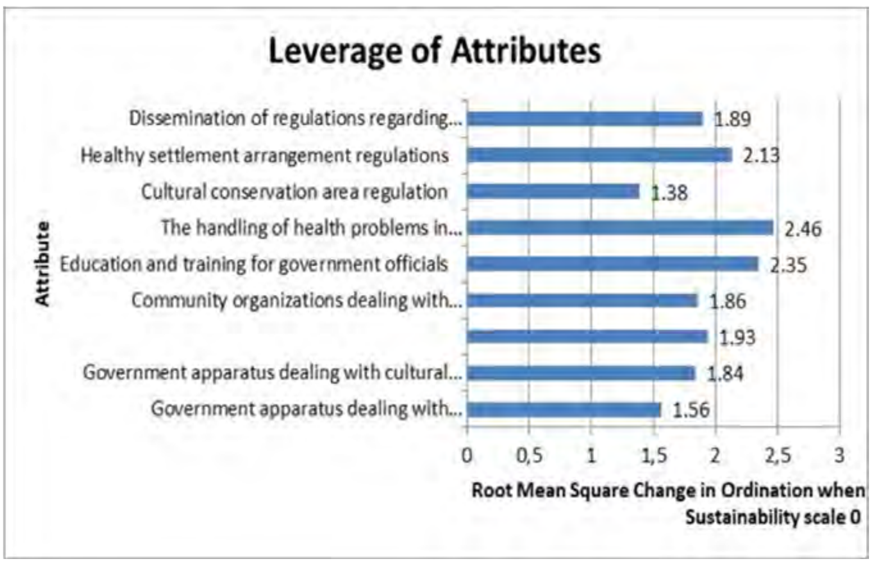

Fig. 9: Sustainability leverage attributes for institutional law dimension

social development innovations. These innovations could increase the independence and well-being of the people of Penyengat Island by adopting community-based approaches (Ikhwan *et al.,* 2021). In addition, cultural resources could improve ecotourism and the quality of life for local residents (Mulyadi, A., 2018). Ultimately, healthy tourism is beneficial in improving the health status of coastal area residents (Wall *et al.,* 2017).

The MDS analysis of the attributes for the Institutional Law dimension recorded the index value and sustainability status in the sufficiently continuous category at all locations (RW1, RW2, RW3, RW4 and RW5). The highest index value was recorded at RW2 (71.24) with sufficiently continuing status (Fig. 8).

The leverage analysis conducted on the institutional legal dimension identified six attributes

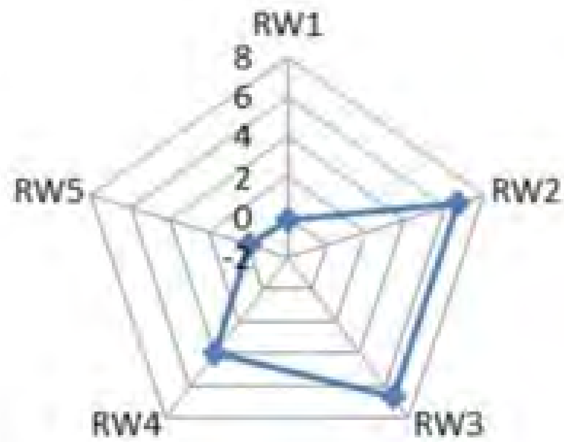

Fig. 10: Kite diagram of the green infrastructure dimension showing the score for the sustainability status of settlement planning on Penyengat Island

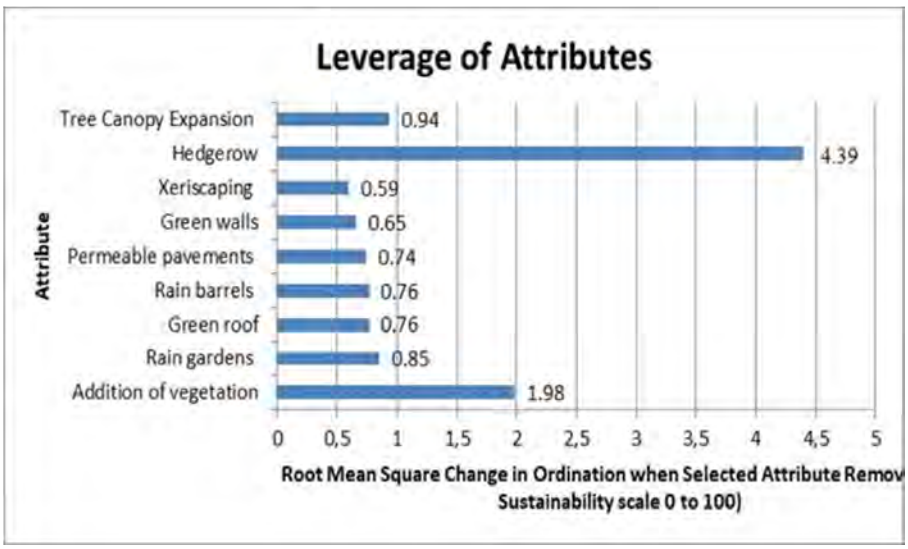

Fig. 11: Sustainability leverage attributes for green infrastructure dimension

as sustainability levers: (1) Handling cross-program problems, (2) Education and training, (3) Settlement regulations, (4) Community organizations regarding settlements, (5) Dissemination of regulations, and (6) Cultural heritage organizations (Fig. 9). It is crucial to establish government regulations policies and strategies that can boost tourism development on Penyengat Island, hence, making the island more accessible to the international community (Kachniewska *et al.,* 2015). Precisely, emphasis on legislative management is essential in dealing with coastal urban problems (Huynh *et al.,* 2015).

The MDS analysis of the attributes for the green infrastructure dimension shows the index value and sustainability status in the unsustainable category at all locations (RW1, RW2, RW3, RW4 and RW5). The lowest index values were recorded at RW1 (-0.12) and RW5 (-0.12) with a discontinued status (Fig. 10).

The leverage analysis conducted on the green infrastructure dimension identified four attributes

Table 9. Comparisons of research results on sustainable health using different methods

Tools	Variables	Implication	Sources
Structural Equation Model (SEM) analysis	Sustainable housing, physical sustainability of housing, environmental sustainability of housing	The results offer valuable insights to support the sustainability of housing in the study area and similar cases, which may vary in different contexts.	Nasrabadi and Hataminejad, 2019
Analytic hierarchy process (AHP)	Housing environment, mobility, community facilities, community social capital	Comparative studies can be applied to other cities in China or Asia.	Wu, 2010
Path analysis	Travellers, locals, resources	This research suggested ecotourism discussion and focus on developing countries, particularly in the Riau Islands, Indonesia.	Aras, 2018
Destination Management Organizations (DMO)	Rural tourism, sustainable development, agro-tourism	This study concluded practical implications for Destination Marketing Organizations (DMOs) and tourism leaders continuously evaluating rural tourism initiatives.	Kachniewska, 2015
Nud.Ist Vivo (Nvivo) 12 plus Critical discourse analysis	Tourism, sustainable development	The practical implication of this paper is to adopt a bottom-up approach for a comprehensive understanding of the alignment of tourism with the SDGs in Abaco Cays.	Francis, 2020
Geografical information system (GIS), Cluster analysis	Groundwater quality, hydrochemistry	The results of this study can be used to develop appropriate water management plans for sustainable development in the region.	Krishnakumar, 2015)
The database is developed in Postgre SQL	Climate change, adaptation, risking it, coastal greening	Community-based climate change strategies and management plans must be effectively implemented to build, monitor, and maintain community infrastructure that helps protect the local population from natural hazards and disasters.	Touhiduzzaman, 2008
Geographic Information System (GIS)	Climate change, vulnerability, coastal erosion, geographic information systems	The three qualitative models, based on a cognitive approach, utilizing a set of parameters determined in this research, serve as effective tools for the spatial distribution of erosion in various mangroves worldwide.	Fernando Morgado, 2017
Balanced scorecard Cronbach's alpha	Critical success factors, key performance indicators, coastal urban projects	Future studies could include other types of marine projects in different regions. Such studies can contribute to the findings of this research.	Nguyen, 2020
Analysis of variances (ANOVA), independent t-test	Climate change, rural development, adaptation of coastal communities	It is recommended that information management activities related to climate change be actively carried out by NGOs, universities, and relevant stakeholders.	Bolong, 2015
EZ-TEXT program	Clean and healthy coastal communities, public response	There is a need for intervention in health education. Government commitment is required to explore the potential of agricultural products as the pharmaceutical industry and to assess and review the relevant regulations concerning healthcare facilities.	Rizal, 2018
Path analysis	Public relations, activities in public spaces, sensitivity to location	The study findings suggest that land development policies should avoid damaging public spaces. Public areas should be developed to facilitate activities that promote citizens' active participation in sustainable community development.	Passanan, 2019
Construction theory grounded approach	Public health, tourism	This study concludes that strategies for engaging in healthy tourism offerings include interventions to curb alcohol consumption, regenerate areas, and promote eudaimonic well-being – which ultimately enhance place perceptions.	Susanna Curtin, 2017
Multi-dimensional scale (MDS), Rapfish analysis	Ecological dimensions, economic dimensions, socio-cultural dimensions, institutional, legal dimensions, green infrastructure dimensions	The research has implications for the sustainability of small islands with historical value while maintaining environmental preservation.	The current study

as sustainability levers: (1) Hedgerow, (2) Additional vegetation, (3) Tree Canopy Expansion, and (4) Rain gardens (see Fig. 11). One of the challenges faced in the settlement arrangement sector in urban areas is the financing for green infrastructure maintenance, posing a major constraint in ensuring the sustainability of green infrastructure in urban settlements (Bagheri *et al.,* 2021). Coastal area planning is key to a comprehensive coastal management system (Liu and Sing, 2019). In addition, seawater adversely impacts the building foundations and infrastructure systems in coastal areas (Elshinnawy and Almaliki, 2019).

CONCLUSION

The arrangement of healthy settlements on Penyengat Island as a cultural heritage has been assessed in different dimensions. The MDS analysis showed that the sustainability value of the ecological dimension ranged from 51.71 – 60.67 with a moderate status at locations RW1 to RW5, while the economic dimension ranged from 40.46 – 48.23 with a less advanced status in all locations. The socio-cultural dimension ranged from 48.97 – 51.78, with sufficient status at RW1 and less sustainable at RW2 to RW5. Meanwhile, the institutional legal dimension ranged from 50.18-71.24, with a sufficiently continuous status in all locations (RW1 to RW5). The green infrastructure dimension ranged from -0.12 – 6.72, with a non-continuous status at locations R1 to RW5. The ecological dimension was quite sustainable at RW1, RW2, RW3, RW4, and RW5 but was categorized as less sustainable in the same locations. In the socio-cultural dimension, RW1 is considered quite sustainable, while RW2, RW3, RW4, and RW5 are classified as less sustainable. In contrast, the institutional, legal dimension is quite sustainable in all locations. The green infrastructure dimension is deemed unsustainable in RW1, RW2, RW3, RW4, and RW5. This research provided a holistic understanding of various attributes from each dimension as determining factors. These attributes could serve as a reference in developing strategies to structure healthy settlements in the coastal areas in the cultural heritage sites of Penyengat Island. The identified leverage attributes that significantly influenced the sustainability of healthy settlement arrangements in the coastal area of Penyengat Island as a cultural heritage include household waste, lighting in the house, noise, residential density, clean water supply, CSR funding support, type of work, increased income, technological innovation, number of tourists, public perception of the distance between cultural heritage and settlements, social conflict, implementation of mutual cooperation, management of community groups, handling cross-program problems, education and training, settlement regulations, community organizations regarding settlements, socialization of regulations, cultural heritage organizations, hedgerow, additional vegetation, tree canopy expansion, and rain gardens. It is essential for the government and relevant stakeholders to prioritize these leverage attributes by developing and implementing appropriate policies. These strategies would ensure the maintenance of sustainable and healthy settlement arrangements in the coastal area of Penyengat Island as a cultural heritage site.

AUTHOR CONTRIBUTIONS

I. Martias conducted the literature review, developed the research design and model, and collected and analyzed the data. R. Rifardi arranged and designed the study. A. Agrina analyzed and interpreted the data. I. Suprayogi prepared the manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication or falsification, double publication and, or submission, and redundancy, have been completely witnessed by the authors.

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ABBREVIATIONS

%	Percent
°C	degrees Celsius
AHP	Analytic hierarchy process
ANOVA	Analysis of variances
CSR	Corporate social responsibility
DMO	Destination Management Organizations
et al.,	And others
EZ-Text	Enterprise Zones Text
Fig.	Figure
GIS	Geographic Information System
Km^2	Square kilometer
MDS	Multi dimensional scale
Nvivo	Nud.Ist Vivo
Rapfish	Rapid Appraisal for Fisheries
Rapsettle	Rapid appraisal for settlement ecosystem
R^2	Coefficient of determination
RW.	Administrative region (Rukun Warga)
SEM	Structural Equation Model
SMP	Junior high school
SQL	Structured Query Language
UNESCO	United Nations Educational, Scientific and Cultural Organization

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SPECIAL ISSUE: (Eco-friendly sustainable management)
ORIGINAL RESEARCH PAPER

Biological control of bacterial wilt in pathumma; Curcuma alismatifolia

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ABSTRACT

BACKGROUND AND OBJECTIVES: In Thailand, bacterial wilt is one of the most severe diseases that affects pathumma, also known as *Curcuma alismatifolia* Gagnep. Biological control was proposed to control this disease with antagonistic bacteria. The current study was conducted to screen for antagonistic microorganisms capable of inhibiting the pathogenic bacteria and to evaluate the beneficial effect of antagonistic bacteria on pathumma *in vivo*.
METHODS: Antagonistic bacteria were isolated from soil samples obtained from several locations in Thailand and screened for antibacterial activity. Next, the optimal conditions for the growth of antagonistic bacteria were determined. The production of anibacterial substances were then characterized. The potential of antagonistic bacteria to reduce the growth of plant pathogens was evaluated under greenhouse conditions.
FINDINGS: In total, 102 bacterial isolates were isolated using tryptic soy medium. After evaluating their capacity to inhibit the growth of the wilt-causing bacteria using the paper disc diffusion assay, it was found that three bacterial isolates, *Bacillus subtilis* SP15*, Pseudomonas mosselii* SP38*,* and *Pseudomonas mosselii* SP46 showed high ability to inhibit growth of the wilt-causing bacteria *Enterobacter asburiae* JK1, JK2, JK3, JK4, *E. dissolvens* JK5 and E. hormachei JK6. The optimal conditions for all antagonistic bacterial isolates were 25 or 30 degrees Celcius, at potential of hydrogen 7-8 in modified tryptic soy medium containing 0.5 percent (weight /volume) glucose or sucrose and 1.5 or 2 percent (weight/volume) peptone. The antagonists were able to produce siderophores and phenazines. Under greenhouse experiments, the mixed cultures of antagonistic bacterial isolates could reduce the wilt disease incidence, and the number of pathogenic bacteria declined compared with the diseased control plants. In addition, it was discovered that soil materials provided the best carrier materials for the successful formulation of the mixed culture of antagonistic bacteria.
CONCLUSION: This study revealed that the selected antagonists were beneficial for controlling wilt disease in pathumma. This is the first scientific study on the control of wilt-disease causing *Enterobacter* spp. in *C. alismatifolia* Gagnep. in Thailand using antagonistic bacteria. It is expected that these antagonistic bacteria be useful in wilt disease management in the field for friendly and sustainable agriculture.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
37	4	3

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INTRODUCTION

Curcuma alismatifolia Gagnep. (Gagnepain) is commonly referred to as the Siam tulip or pathumma, and it is a native plant of Southeast Asia. An attractive flower, it is reminiscent of a cluster of tulips (Ruamrungsri, 2015). Pathumma belongs to the family Zingiberaceae and is a plant that is frequently found in northern and northeastern Thailand. Both in Thailand and worldwide, the popularity of these beautiful plants has increased. Rhizomes are exported for around United Stae Dollar (USD) 38.1 million each year (Boontiang, 2021). Moreover, scientific documents have revealed that *C. alismatifolia* leaves have effective antidiarrheal and antioxidant properties as do other Curcuma plants (Ruamrungsri, 2015). Pathumma is susceptible to wilt disease, which has caused widespread destruction. The wilt bacteria overwinters in plant debris in soil, seeds, vegetative propagative materials, or insect vectors. They enter the plants through wounds that expose vascular elements and multiply and spread in the latter. They spread from plant to plant through the soil, handling and tools, direct contact of plants, or insect vectors. Control of bacterial vascular wilt is difficult and depends primarily on the use of crop rotation, resistant varieties, bacteria free seed or other propagative material, removal of the infected plant debris, and proper sanitation. Among several wilt diseases causing Gram-negative plant pathogens, *R. solanacearum* has been intensively studied both in biochemical and genetical aspects and has long been recognized as a model system for the analysis of pathogenicity. *Ralstonia* (formerly *Pseudomonas*) *solanacearum*, the causal agent of bacterial wilt, was ranked as one of the world's most important phytopathogenic bacteria prevalent in tropical, subtropical and some warm regions of the world. Moreover, it can also occur in cool temperate areas. The original habitat of this organism is probably the tropics, but its increasing occurrence in geographical regions with a prevailing temperate climate has resulted in speculations about its adaptation to these conditions, and its establishment. The bacteria can cause devastating problems in agriculture resulting in major losses to farmers (Promsai *et al*., 2012). *Enterobacter* sp. is a Gram-negative, rod-shaped, and facultative anaerobic bacteria. Based on molecular and taxonomy investigations, it was previously assigned to the genus Erwinia but has since been reassigned to the genus *Enterobacter*. According to several findings, *Enterobacter* spp. could cause bacterial wilt in crops globally. Some strains of *E. mori* have been associated with wilt disease of strawberry in China (Ji *et al*., 2023). Internal papaya fruit yellowing triggered by *E. sakazakii*. *Enterobacter* sp. causes patchouli wilt disease in Indonesia (García-González *et al*., 2018; Zulfadli *et al.,* 2023). Soil-borne pathogens are difficult to control because they attack plants via soil over long periods of time. Chemical control has several limitations, including a negative public attitude and associated environmental concerns. Agrochemical treatment adversely impacts the environment, with residue persistence, the reduced variety of nontarget organisms, resistance, and the shifting of the farming area (Rodelo-Torrente *et al*., 2022). The use of biological control agents in sustainable agriculture is growing as a result of the practice to limit the use of pesticides and the environmental residues they produce (Ehzari *et al*., 2022). Future sustainable agriculture will increasingly rely on the integration of biotechnology with traditional agriculture (Abo-Elyousr *et al*., 2022; Samimi *et al.,* 2023). The most sustainable and environmentally acceptable control may be achieved using biocontrol agents due to the effort to reduce the use of agrochemicals (Ilmasari *et al*., 2022) and their residues in the environment and in food (Sánchez-Hernández *et al*., 2022). Plant pathologists have been fascinated by the idea that such microorganisms could be used as environmentally friendly biocontrol agents that have no effect on nontarget organisms (Ruanpanun and Nimnoi, 2020; Sivakumar *et al.,* 2022; Dhayalan and Sudalaimuthu, 2021). Antagonistic microorganisms have emerged as an alternative management strategy. Among several biological control agents, *Bacillus* and *Pseudomonas* are potential agents to use against plant pathogens, since they can produce various substances such as antibiotics and siderophores (Promsai *et al*., 2023; Zhang *et al*., 2023). Complete eradication of wilt disease in the pathumma production chain has still not been achieved. Despite extensive studies on the pathogenesis, epidemiology, and control, bacterial wilt remains an important problem worldwide. The objectives of the current study were to screen for antagonists that could inhibit wilt-causing bacteria and to evaluate the beneficial effect of antagonistic bacteria on pathumma *in vivo* in 2012.

MATERIALS AND METHODS

Wilt-causing bacteria cultures and plant materials

Wilt-causing bacteria were isolated from infected pathumma rhizomes. The Triphenyltetrazoliumchloride (TZC) medium containing 0.1% weight per volume, (w/v) peptone, 0.05 percent (%) (w/v) glucose, 0.01% (w/v) pancreatic digest of casein, and 0.005% (w/v) 2, 3, 5 – triphenyltetrazoliumchloride (Sigma–Aldrich, USA) was used as the culture medium. The selected wilt-bacteria were used to reinfect pathumma plants and were conventionally and molecular identified described by Promsai *et al*. (2012). The pathogenic bacteria used in this study were *Enterobacter asburiae* JK1, JK2, JK3, and JK4, *E. dissolvens* JK5, *E. hormachei* JK6, and *Ralstonia solanacearum* R227 as standard cultures obtained from the Ministry of Agriculture and Cooperatives, Thailand. Pathumma rhizomes were obtained from the Bua Lai Pathumma Garden, Chiang Mai, Thailand. Pathumma rhizomes were cultivated at the beginning of May in greenhouse conditions at the Faculty of Science, Chiang Mai University.

Isolation and screening of antagonistic bacteria

Soil samples from different parts of Thailand were collected for bacterial isolation using tryptic soy broth (TSB, Merck, Germany). One gram of each soil sample was put into 5 mL of TSB and then incubated at 30, 37, and 45 degrees Celsius (°C) for 48 hours (h). The microbial cultures were streaked on tryptic soy agar (TSA) under the previous conditions to achieve the pure isolate. Random colonies were selected from agar plates in a variety of sizes, shapes, and colors. For further investigation, each pure isolate was kept at 4°C and -20°C in 20% glycerol. Agar disc diffusion was used to test each bacterium's ability to inhibit the growth of the wilt-causing bacteria. Each isolated bacterium was cultivated in TSB at 30°C for 48 h. After that, the culture broth was centrifuged at 3,000 x*g* for 10 minutes (min.) Concomitantly, the pathogenic bacteria were cultivated in TZC broth at 30°C for 12 h (At 660 nm, the optical density was 0.5, corresponding to approximately $1x10^6$-$1x10^7$ colony forming units per milliliter (cfu/mL) prior to swabbing onto TZC agar plates. A paper disc with a diameter of 6 mm (Macherey-Nagel, Germany) was immersed into the obtained bacterial supernatant before being put onto the surface of the previously prepared plate. A negative control was performed using the TSB medium. The tested plates were incubated for 24-48 h at 30°C before being checked for the presence of clear inhibitory zones. The radius of the inhibition zone, measured in millimeters, was used to evaluate the degree of bacterial wilt inhibition. Accordingly, the antagonistic bacteria were determined from among the bacterial isolates that initially underwent preliminary screening and demonstrated positive *in vitro* inhibitory activity. The potential antibacterial agents that showed a high level of inhibition were kept and further evaluated.

Identification of antagonistic bacteria

The selected bacterial isolates that exhibited a high level of inhibition were identified using the conventional and molecular methods.

Conventional method

According to traditional morphological characteristics such as the colony growth pattern, pigment production, and spore formation, antagonistic strains (the isolates SP15, SP38, SP46, and SP58) were preliminarily identified. Biochemical characteristics were observed, i.e., catalase (Univar, Australia), lysine decarboxylase (Sigma–Aldrich, USA), phenylalanine deaminase (Sigma–Aldrich, USA), oxidase, motility, methyl red (Univar, Australia), and Voges-Proskauer (Univar, Australia) test; production of indole (Univar, Australia), lecithinase (Sigma–Aldrich, USA) and gas from glucosa; utilization of gelatin (Univar, Australia), starch (Univar, Australia) and casein (Univar, Australia); growth in TSB containing 2, 5, 7, and 10% NaCl (Univar, Australia); growth at 30, 40, 50, and 55°C; utilization of citrate, adonitol, alanine, arginine, mannitol, rhamnose, ribose, sucrose, trehalose, and xylose (Univar, Australia) (Promsai *et al*., 2018).

Molecular method

Total genomic DNA samples of the isolates SP15, SP38, SP46, and SP58 were extracted from fresh culture following Chumphon *et al*., (2022) with some modifications. A 16S rDNA (~1.5 kb) was amplified using the universal primer, 20F (5'-AGTTTGATCCTGGCTC-3') and 1540R (5'-AAGGAGGTGATCCAGCC-3') (Promsai *et al*., 2023). The PCR conditions consisted of a 1 min. initial denaturation at 94°C, followed by 35 cycles of a 1 min. denaturation at 94°C, a 2 min primer annealing at 58°C, a 2 min extension at 72°C, and a final 7 min extension at 72°C. PCR (polymerase chain reaction) products were purified using a Gel/PCR DNA Fragments Extraction Kit (Geneaid, Catalog no. DF100). The obtained PCR products were analyzed by First Base Company, Malaysia, for nucleotide sequencing. The BLAST analysis was performed on the nucleotide sequences of the 16S rRNA gene to determine their identities. The ClustalW software was used to align the nucleotide sequences. The neighbor-joining (NJ) phylogenetic tree was constructed using the program in MEGA X. A topological study was conducted with 1,000 bootstrap repetitions.

Production of siderophores

Screening of siderophore production

Production of siderophores was preliminarily examined according to the modified universal chrome azurol S (CAS, Sigma–Aldrich, USA) assay method. Siderophore production was tested on modified Gaus No.1 medium (MGs) containing CAS. Pure isolate samples of SP15, SP38, SP46, and SP58 were stabbed on CAS-agar and incubated at 30°C for 72 h. Orange, purple, or yellow surrounding colonies were regarded as siderophore-producing isolates (Hofmann *et al*., 2021). The bacterial isolates which changed the medium color, were secondarily detected for siderophore type and concentration.

Detection of the chemical nature of siderophores

The positive isolates were cultured in MGs-1 broth and incubated at 30°C for 48 h with agitation of 150 rpm. Turbimetric monitoring of the population density at 660 nm was performed throughout the incubation. The centrifugation at 3,000 x*g*, 4°C, for 10 min was conducted to separate the bacterial cells. The obtained supernatants were concentrated using an ultrafiltration technique prior to the detection of the nature of the siderophores (catecholates and hydroxamates) using chemical assays.

Catecholates: Catecholate-type detection was performed according to Grobelak and Hiller (2017) with some modifications. A mixture comprising 50 microliters (µL) of culture supernatant, 50 µL of 0.5 molarity (M) hydrochloric acid (HCl) (RCI Labscan, Thailand), and 50 µL nitritemolybdate reagent was poured into 96-well microplates. When the yellow color appeared, 50 µL of 1 M NaOH (RCI Labscan, Thailand) was added. To allow a complete reaction, the plates were continuously incubated at room temperature for 5 min. The absorbance of red pigment was measured at 500 nanometers (nm) with the uninoculated media mixed with a reagent as a blank. The level of catecholate produced was estimated against a standard of 2,3-dihydroxybenzoic acid (Sigma–Aldrich, USA).

Hydroxamates: Hydroxamate-type siderophore detection was performed using ironperchlorate assay (Radhakrishnan *et al*., 2014) with some modifications. A total of 30 mL of the supernatant was added to 150 µL of ferric perchlorate (Univar, Australia) solution and incubated at ambient temperature for 5 min. The presence of a hydroxamate-type siderophore was shown by the development of an orange-red color. Measurement of absorbance at 480 nm was used to calculate the concentration of hydroxamate. The uninoculated medium mixed with the reagent was used as a blank. The level of hydroxamate produced was estimated against a standard deferoxamine mesylate (Sigma–Aldrich, USA).

Production of phenazines

The production of phenazine antagonistic bacterial isolates SP15, SP38, SP46, and SP58 were determined using thin layer chromatography (TLC) (Karmegham *et al*., 2020). Each isolate was streaked onto King's B (KB) agar plates. To remove the bacterial cells, sterile water was used to wash the bacterial colonies grown on agar plates. The tiny pieces of agar were excised and collected in an Erlenmeyer flask. The suspension was added with 12 mL of chloroform and was then incubated at 37°C for 2 h with shaking. Mixing the chloroform layer with an equivalent volume of 0.1 M NaOH was done. The phenazine compound shifted to the aqueous phase. The chloroform fraction was air-dried and dissolved in methanol (RCI Labscan, Thailand). For the chromatographic analysis, the methanol extract was spotted carefully on TLC plates (silica gel 60 F_{254}). The silica plates were then placed in a mobile-phase solvent containing toluene/acetone (3:1 volume per volume, v/v) (RCI Labscan, Thailand) and detected under UV light for phenazine observation.

Optimization of inhibitory substances produced by antagonistic bacteria

Four antagonistic bacteria (SP15, SP38, SP46, and SP58) were selected for optimization. Various carbon and nitrogen sources were added to the basal medium in order to evaluate the medium optimization process. The zone of inhibition (ZOI) was used to determine the effectiveness of the improved medium (Promsai *et al*., 2023).

Carbon sources

The antagonistic strains were grown at 30°C in an Erlenmeyer flask containing 50 ml modified TSB in which the glucose was substituted with sucrose, maltose, fructose, galactose, lactose, mannitol or sorbitol (Sigma–Aldrich, USA). After 48 h of incubation, each culture was centrifuged to collect the supernatant for further use with the agar disc diffusion method against four isolates of wilt-causing bacteria *Enterobacter asburiae* JK1, JK2, JK3, and JK4 The modified TSB with various carbon sources substituted for the glucose was used as a negative control. The most effectively inhibiting carbon source was selected for further evaluation of the optimal concentration: 0.1, 0.5, 1.0, 1.5, 2.0, or 2.5% (w/v).

Nitrogen sources

The antagonistic strains were grown at 30°C in an Erlenmeyer flask containing 50 ml modified TSB in which peptone was substituted with yeast extract, tryptone, corn flour, corn steep liquor, ammonium dihydrogenphosphate, $NH_4(H_2PO_4)$, or ammonium nitrate (NH_4NO_3) (Himedia, India). The modified TSB was a negative control. The most effectively inhibiting carbon source was selected for determination of the optimal concentration; 0.1, 0.5, 1.0, 1.5, 2.0, or 2.5 % (w/v). Cultures were centrifuged to obtain the supernatant and tested for the growth inhibition of pathogenic bacteria.

Media potential of hydrogen (pH)

To determine the optimal media pH of the culture medium, antagonistic strains were cultivated in 50 mL modified medium with the pH adjusted to 4, 5, 6, 7, 8, 9, 10, or 11. The obtained supernatants were tested for the growth inhibition of pathogens. The modified TSB samples at various pH levels were used as a negative control.

Temperature

The tested temperatures were 25, 30, 37, or 45°C. The antagonistic strains were cultivated in 50 mL of modified medium. After 48 h of incubation, each culture broth was centrifuged to obtain the supernatant, which was further investigated for its activity with the ZOI. The modified TSB with the optimal carbon source, nitrogen source, and media pH was used as a negative control. The antagonistic strain was then cultivated in the most effective medium after finding the optimal medium for the optimal growth of cells and antibacterial activity.

Evaluation of antagonistic bacteria in the control of bacterial wilt under greenhouse conditions

Three antagonists were mixed and cultivated in 100 ml of modified TSB obtained from the earlier study. The antagonist cultures were grown at 30°C for 24 h. To prepare wilt-bacterial inocula, each pathogenic bacterial isolate was grown in TZC broth at 30°C for 24 h. The concentrations of the antagonistic mixed-culture and wilt-causing bacteria were approximately $1x10^7$ - $1x10^8$ cfu/mL. The rhizomes were planted in 15cm-diameter plastic bags containing sterile soil created from commercial soil mixed with 3:1:1 ratios of chaff and coir. The rhizomes and pseudostems of pathumma were wounded prior to drenching with the bacterial inocula. The experiments were conducted in a greenhouse at the Faculty of Science, Chiang Mai University. Three experiments were performed.

Experiment 1

Pathumma rhizomes and soil in pots were co-applied with antagonistic and pathogenic bacteria prior to cultivation.

Experiment 2

Samples of shooting pathumma were treated with both antagonistic and pathogenic microorganisms.

Experiment 3

Before pathumma cultivation, pathogenic bacteria were introduced to rhizomes and the soil, and after plant germination, mixed cultures of antagonistic bacteria were introduced to the plant pots.

The number of both antagonistic bacteria and pathogenic bacteria was assessed in each trial using the serial dilution method and spread on TSA and TZC agar plates. The viable cell count of bacteria and growth plant evaluation were performed every 15 days for 5 months. All treatments were replicated three times. To count the number of live bacterial cells in the soil mix, core samples from each infested bag were taken using a spatula. A test tube containing

Table 1: Assessments of antimicrobial activity, siderophores and phenazine of selected antagonistic bacteria[a,b]

Bacterial isolate	Sources	Growth inhibition of wilt bacteria (mm)	Siderophore production				Phenazine production
			Hydroxamate conc. (µM)		Catecholate conc. (µM)		
			Culture broth	Concentrated culture broth	Culture broth	Concentrated culture broth	
SP15	Hot spring	13.5±0.5a	5.00±2.12a	10.00±3.68a	1.64±0.5a	1.90±0.39a	-[c]
SP38	Rain tree	19.0±1.9b	27.12±5.68b	41.00±3.37b	3.50±0.3c	4.24±0.52c	+
SP46	Banyan tree	20.0±3.5b	45.87±6.12c	63.87±6.57c	1.75±0.1a	2.25±0.32a,b	+
SP58	Banyan tree	19.0±3.5b	49.50±7.64c	70.75±4.49d	2.69±0.9b	2.71±0.42b	+

[a] Results are shown as mean ± standard error
[b] Means followed by the same letter within a column are not significantly different (Tukey's Test, *P*=0.05)
[C] Phenazine production; " + " phenazine positive, " - " phenazine negative

9 mL of sterile water and 1 g of soil was added. The solution was agitated and serially diluted prior to spreading on TSA and TZC agar plates containing 100 micrograms per milliliter (µg/mL) cycloheximide (Sigma–Aldrich, USA). The agar plates were then incubated at 30°C for 48 h, and the number of bacteria was calculated in cfu units. The bacterial population data were transformed to $\log_{10}$ values (Swe *et al.*, 2023). The numbers of total bacteria and wilt-causing bacteria were counted on the TSA and TZC plates, respectively, with morphological characteristics observed. Consequently, the numbers of antagonistic bacteria were calculated by subtracting the number of wilt-causing bacteria from the total number of bacteria. The occurrences of wilt disease and the growth of plants were assessed. The disease incidence (DI) was calculated using the following equation (Vinayarani and Prakash, 2018).

DI = Number of infected plants/number of all inoculated plants x 100.

All experiments were conducted in 3 years of planting (trials 1, 2 and 3).

Designation of mixed culture products

Three carrier materials, chaff, coir, and soil were accessed for their capacity to support the growth of antagonistic bacteria. The isolates SP15, SP38, and SP46 were cultured on TSB and incubated at 30°C for 24 h. To separate the bacterial cells, the culture was then centrifuged at 3,000 x g for 10 min. The cell pellets were mixed with sterile distilled water. The individual suspension or a suspension made from a mixture of the four antagonistic cells containing $1x10^8$ cfu/mL was added into 100 g of the carrier materials and mixed well under sterile conditions. The materials were then incubated at ambient temperature for 60 days. The viable cell count was determined every 15 days of storage.

Statistical analysis

A one-way analysis of variance (ANOVA) was used to statistically analyze the data using the SPSS software version 20 for Windows. Tukey's test was conducted, and the means were compared at $P < 0.05$.

RESULTS AND DISCUSSION

Isolation and screening of antagonistic bacteria

One hundred and two bacterial isolates were isolated from seven soil samples obtained in Thailand at various locations and 55 isolates were Gram-positive and rod-shaped, and 47 isolates were Gram-negative and rod-shaped. From the result of the growth inhibition of the plant pathogens (*E. asburiae* JK1, JK2, JK3, JK4, *E. dissolvens* JK5 and *E. hormachei* JK6), only four isolates (SP15, SP38, SP46, and SP58) that were isolated from soils collected from the Sankumpang hot spring, Srinakarin Dam, and Bangsai Arts and Crafts Centre displayed a high ability to make a clear inhibitory zone of 13-23 mm in diameter (Table 1). The four bacterial antagonists showed different degrees of antagonism, and there was a slight difference between the six strains of pathogenic bacteria. The results indicated that the microorganisms isolated from soils had a high capacity to suppress the growth of wilt-bacterial strains. This conclusion was supported by the fact that plant-growth-promoting rhizobacteria (PGPR) exhibited the colonization of roots, encouraging plant development and/or lowering the prevalence of plant disease (Vinayarani and Prakash, 2018). Dong *et al*. (2023) revealed that *Bacillus velezensis* RC116 could inhibit the growth of wilt-disease bacteria in tomato. RC116 not only produced protease, amylase, lipase, and siderophores but also secreted indoleacetic acid and dissolved organophosphorus *in vivo*. The biocontrol marker genes associated with antibiotics biosynthesis could be amplified in the RC116 genome. Extracellular secreted proteins of RC116 also exhibited strong lytic activity against *Ralstonia solanacearum* and *Fusarium oxysporum* f. sp. *Lycopersici*. This antagonist was likewise successful at preventing the pathogen's growth and survival both *in vitro* and *in vivo*. It may be possible that there was no disease in the area where the antagonists were isolated. The prospective antibacterial agents with high levels of inhibition were maintained, and further *in vivo* evaluation was undertaken in the greenhouse.

Identification of antagonistic bacteria

The bacterial isolate SP15 was Gram-positive and rod shaped with ellipsoidal endospores located at the cell terminal, oxidase negative, catalase positive, and non-motile. Its microscopic size was 0.5-1.5 µm x 1.0-3.0 µm (width x length). The strains SP38, SP46, and SP58 were Gram negative, short-rodshaped, facultative anaerobe, oxidase positive, and motile. Their microscopic sizes were 0.5-1.0 x 1.0-2.5 µm (width x length). Three bacterial isolates, SP38, SP46 and SP58 were classified as *Pseudomonas,* since they produced oxidase and could not ferment lactose. However, they could not be identified to the species level by using the conventional method due to the complexity of the genus *Pseudomonas*. All strains were repeatedly confirmed using 16S rRNA gene determination. Partial 16s RNA sequencing was used to identify the antagonistic bacterial isolates to the species level and to determine whether there were clusters of similar organisms. From the Genbank database similarity and a neighbor-joining tree (Fig. 1), it was revealed that the isolates SP15, SP38, SP46, and SP58 were *Bacillus subtilis*, *Pseudomonas mosselii*, *Pseudomonas mosselii*, and *Pseudomonas aeruginosa*, respectively. Identification of the prospective biocontrol agents requires the efficient isolation of microorganisms from the rhizosphere of various crops. The largest potentially most promising group of rhizobacteria used in the biocontrol of plant diseases is fluorescent *Pseudomonas* spp., one of the bacterial biocontrol agents. These bacteria rapidly and actively colonize the root, thereby becoming excellent soil inocula. (de Oliveira *et al*., 2022). *Bacillus* spp. have been studied extensively for many years. *Bacillus* spp. and *Pseudomonas* spp. as biocontrolling organisms agreed with other observations. For example, these following references reported biocontrol activity. *B. licheniformis* and *B. aerius* had a high potential for antifungal activity against *Podosphaera xanthii*, a pathogen causing powdery mildew in cucumber (Abo-Elyousr et al., 2022). *B. subtilis* EA-CB0015 exhibited the growth inhibition of *Botrytis cinerea* and *Colletotrichum* sp. (Arroyave-Toro *et al*., 2017). Also, root bacteria including *Pantoea*, *Cronobacter*, and *Pseudomonas* could effectively control *Fusarium oxysporum* f. sp. *cucumerinum*, wilt-causing fungi in cucumber (Zhang *et al*., 2023). However, *Bacillus* and *Pseudomonas* usually inhibited some fungal and bacterial pathogens. The scientific documentation of these bacteria in *Enterobacter* control is limited. The current study seems to be the first report showing *B. subtilis* and *Ps. mosselii* antagonism to *Enterobacter* in pathumma and suggests that the selected isolates have excellent promise for pathumma bioprotection or for use in integrated disease management. To demonstrate effectiveness under bacterial mechanisms, more research is still required.

Production of siderophores

Four isolates of antagonistic bacteria were preliminarily screened for siderophore production on MGs-1 medium containing CAS. All antagonists were grown on CAS agar and showed yellow- and pink-zone surrounded bacterial colonies. The culture supernatants were further characterized for hydroxamate or catechol compounds. The level of hydroxamate and catecholate production was 5.0-49.5 µ*M* and 1.6-3.5 µ*M*, respectively (Table 1). Between the antagonistic isolates, the capacity to produce the siderophore was broadly distributed. Moreover, when the twofold concentrated broth cultures of each antagonistic bacterium were tested, the ultrafiltrates of bacterial supernatants demonstrated a higher level of siderophore concentration in the ranges 10.0-70.8 µ*M* and 1.9-4.2 µ*M*, respectively. These results indicated that the ultrafiltration technique was very beneficial for metabolite concentration. The results from the qualitative and quantitative estimations

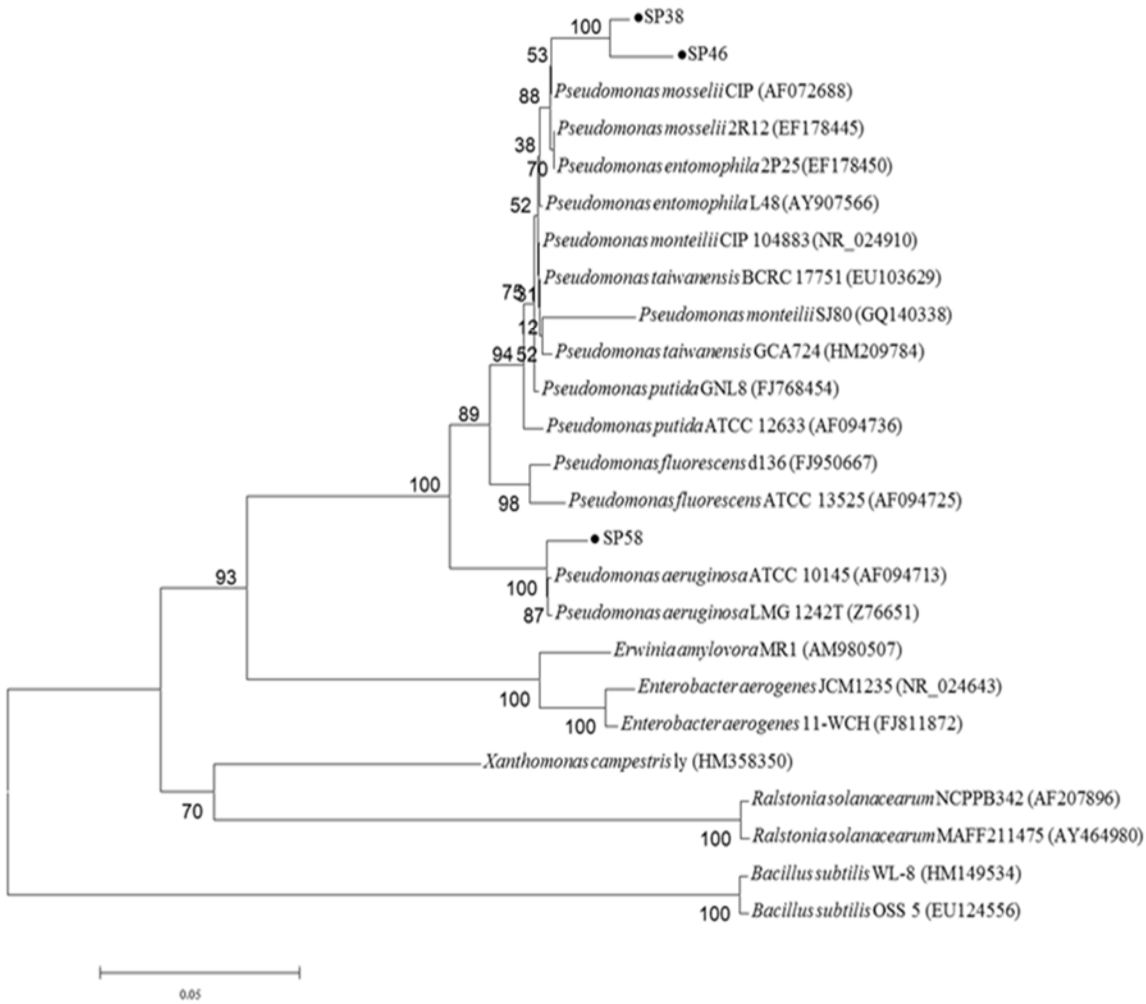

Fig 1: A neighbour-joining tree illustrating the position of the antagonistic bacterial isolates including SP38, SP46 and SP58 based on 16S rRNA gene sequences was constructed. 1,000 replicates were used to generate the bootstrap values, and the bar indicates 0.02 substitution per nucleotide position. In parenthesis, the GenBank accession numbers were displayed.

of siderophore production by *B. subtilis* SP15, *Ps. mosselii* SP38, *Ps. mosselii* SP46, and *Ps. aeruginosa* SP58 showed that they were powerful producers of siderophores. Several published studies have reported the ability of *Bacillus* spp. and *Pseudomonas* spp. to produce siderophores. Radhakrishnan *et al.* (2014) demonstrated that a bacterium producing siderophore *Bacillus* sp. SD12 had a high ability to reduce the growth of *Phythium* sp., *Aspergillus niger*, and *Fusarium solani*. This bacterium was isolated from iron factory soil. Siderophores are themselves growth inhibitors of various phytopathogenic fungi, such as *Phytophthora parasitica*, *Phythium ultimum*, and *Fusarium oxysporum* veri *dianthi*. A direct correlation was established *in vitro* between siderophores' synthesis in fluorescent pseudomonads and their capacity to inhibit the germination of chlamydospores of *F. oxysporum*. In antifungal activity testing, the partially purified siderophores inhibited the growth of phytofungal pathogens such as *Fusarium solani*, *Aspergillus niger*, and *Phythium* sp. Subramanium and Sundaram (2020) discovered that siderophore producing *Pseudomonas* spp. (*Ps. aeruginosa* PSA01 and *Ps. fluorescences* PSF02) isolated from rhizospheric soil could inhibit the growth of *Fusarium oxysporum*. Both isolates proved to produce siderophores and solubilized phosphate. A pot experiment resulted in the promotion of the growth of *Arachis hypogaea*. The inoculated PSA01 and PSF02 significantly increased in the root length, shoot length, fresh weight, dry weight, and iron and oil content as compared to the untreated control. This realization is particularly considered to be important to understand siderophore production by *P. aeruginosa*. From the results of the siderophore characterization, although the bacteria grew well in the culture medium, and some antagonistic strains secreted trace amounts of siderophore, they were still considered positive siderophore-producing isolates. Siderophore is a secondary metabolite; a microorganism will produce secondary metabolites whenever its growing rate slows. Because of this, there is no relationship between siderophore concentration and bacterial turbidity. In addition, *Bacillus subtilis* SP15 showed a large positive reaction on CAS agar, but it produced small amounts of hydroxamate and catecholate. It is suggested that detection in liquid media should be used to confirm siderophore production. The sensitivity of the chemical reaction method was higher than the CAS agar plate assay in terms of the low accumulation of siderophores (Arora and Verma, 2017). The resulting siderophore production suggested the hypothesis that bacteria that promoted plant growth or suppressed disease were dependent on the iron concentration. The formulation of high siderophore-producing *P. aeruginosa* F2 and *P. fluorescens* JY3 strains reduced the damping-off incidences caused by *F. oxysporum* and *Rhizoctonia solani* (Abo-Zaid *et al*., 2020).

Phenazine production

By using pigment detection under UV light at 254 nm, the antagonists were initially screened for the synthesis of phenazine with KB plates. Among the four antagonists, only three strains, *Ps. mosselii* SP38, *Ps. mosselii* SP46, and *Ps. aeruginosa* SP58, showed fluorescent UV absorbance. The only positive pigment-producing isolates *Ps. mosselii* SP38, *Ps. mosselii* SP46, and *Ps. aeruginosa* SP58 were then tested on TLC and the antagonistic substance chromatographs were compared to standard chemicals. It was found that both the antagonistic and reference compounds behaved similarly. UV-light analysis of the silica plates revealed a 2-hydroxyphenazine spot (R_f = 0.39) for substances from *Ps. mosselii* SP46 and *Ps. aeruginosa* SP58. Phenazine-1-carboximide (PCA) spots (R_f = 0.82) were displayed only in the standard compound. Meanwhile, *Ps. mosselii* SP38 and the standard compound showed the spot at R_f = 0.65. It was found that only the antagonistic bacteria *Ps. mosselii* SP38, *Ps. mosselii* SP46, and *Ps. aeruginosa* SP58 could produce phenazine derivatives. However, the production and characterization of phenazine compounds should be further studied using HPLC (high-performance liquid chromatography), mass spectrometry, or NMR (Nuclear magnetic resonance spectroscopy) techniques. Earlier studies of phenazine-producing pseudomonads have been published. Karmegham *et al*. (2020) revealed that *P. aeruginosa* VSMKU1 had a strong and broad-ranging antifungal metabolite and could be applied to treat sheath blight disease in rice. The growth of *R. solani* could be inhibited by antifungal agents, and the presence of the gene encoding phenazine-1-carboxamide in the strain VSMKU1 contributes to this fact. The phenazine compound from VSMKU1 significantly arrested the growth of *R. solani* compared to carbendazim by the well diffusion method. These results emphasized that the VSMKU1 isolate can be used as an alternative potential biocontrol agent against sheath blight of rice, instead of using commercial fungicides such as validamycin and carbendazim, which cause environmental pollution and health hazards. The antibacterial substance produced by *Streptomyces* B-92 was characterized as 4-(3S,4R,5S)-3,4,5-trihydroxy-6-(hydroxymethyl) tetrahydro-2Hpyran-2-yloxy) phenazine-1-carboxylic acid. An *in vitro* antimicrobial assay showed that bioactive compound of *Streptomyces* sp. strain UICC B-92 exhibited antagonistic activities against two Gram-positive bacteria, *B. cereus* strain ATCC 10876 and *S. aureus* strain ATCC 25923. The bioactive compound of Streptomyces sp. strain UICC B-92 is suggested as a new compound based on glycoside structure and its position. This novel compound possesses potential in the discovery of new agrichemical and medicinal compounds (Pratiwi *et al*., 2020). Four antagonistic bacterial isolates demonstrated the capacity to synthesize siderophore or phenazine, two highly effective antibacterial substances. This suggested that the antagonistic strains have great potential

Table 2: Summary results of antimicrobial product optimization

Antagonistic isolate	Optimum compositions and conditions					
	C-source	C-source (%)	N-source	N-source (%)	pH	Temperature (°C)
SP15	glucose	0.5	peptone	2.0	8	30
SP38	sucrose	0.5	peptone	2.0	7	25
SP46	glucose	0.5	peptone	1.5	7	25
SP58	sucrose	0.5	peptone	1.5	7	25

for application as a biocontrol agent in pathumma plant *in vivo*. To demonstrate the potential of these organisms for the biocontrol of undesirable microbes and for the encouragement of plant growth, which may be important in agricultural fields in the future, additional in-depth research is needed. The inhibitory substance might be derived from a chemical technique or genetically modified microbes. The substance or an analogous one could be applied as a pesticide.

Optimization of the inhibitory substances produced by antagonistic bacteria

The optimization of the media and growth conditions can significantly improve the yields of microbial metabolites and reduce the overall cost of microbial metabolites (Bellebcir *et al*., 2023). This current study evaluated the type and concentration of carbon sources and nitrogen sources for applying the modified media that exhibited the highest capacity to inhibit the growth of plant pathogens. The pH of the media and the temperature of cultivation were also studied.

Effect of the carbon sources

The influence of carbon sources on the production of antibacterial activity was investigated using basal medium in which glucose was substituted by various carbon sources. The zone of inhibition was assessed. The best type and concentration of the carbon sources were selected under the highest value of antimicrobial activity that was significantly different. If the highest value of ZOI was not significantly different, the suitable source was selected for not only being low cost but also for being more commercially available. The highest antimicrobial activity production levels of *B. subtilis* SP15, *Ps. mosselii* SP38, *Ps. mosselii* SP46, and *Ps. aeruginosa* SP58 were obtained in media containing 0.5% glucose, 0.5% sucrose, 0.5% glucose, and 0.5% sucrose (w/v), respectively (Table 2). It is interesting to note from the optimization results that these antagonists required a simple carbon source such as glucose and sucrose at low concentration. This result was associated with the findings of Mosquera *et al*. (2014) that glucose was the best carbon sources for antimicrobial substance production against the phytopathogen *Mycosphaerella fijiensis*. The antimicrobial activity was 1.2-fold higher in the modified culture medium.

Effect of the nitrogen sources

Among the seven types of nitrogen sources (peptone, ammonium dihydrogen phosphate, ammonium nitrate, corn flour, corn steep liquor, tryptone, and yeast extract), peptone demonstrated the highest antibacterial activity for all antagonistic isolates. The suitable nitrogen sources of *B. subtilis* SP15, *Ps. mosselii* SP38, *Ps. mosselii* SP46, and *Ps. aeruginosa* SP58 were obtained in media containing 2, 2, 1.5, and 1.5% (w/v) peptone, respectively (Table 2). As a result of the presence of a ZOI, the organic nitrogen sources consisting of yeast extract, tryptone, and peptone had a greater advantage than inorganic sources as they also had trace minerals and ions that could enhance the production of enzymes. Similar studies have been reported; Mosquera *et al*. (2014) assessed the suitable culture medium for *B. subtilis* strain EA-CB0015 and found that the medium consisted of 32.5 g/L of yeast extract, demonstrating a 1.2 times increase in antifungal inhibition. The ability of inorganic nitrogen sources to act as direct sources of amino acids' synthesis or their potential role as antibiotic precursors may have contributed to their effectiveness.

Effect of the media pH

The suitable pH levels of the media for antibacterial production by *B. subtilis* SP15, Ps. mosselii SP38, *Ps. mosselii* SP46, and *Ps. aeruginosa* SP58 were a pH of 8, 7, 7 , and 8, respectively (Table 2). The ZOI values of the media at pH 8, 9, 10, and 11 were significantly higher than for the other media. The medium with pH 8 was selected for cultivation because it had a near neutral pH, which was suitable for bacterial growth and easy to prepare. The results showed that the inhibition zones produced by antagonists were moderately different at various pH values. Almost all antagonistic bacteria had high antimicrobial substance production at a neutral pH ranging from 6 to 8.

Effect of the cultivating temperature

The optimum temperature for the cultivation of *B. subtilis* SP15 was 30°C, whereas for *Ps. mosselii* SP38, *Ps. mosselii* SP46, and *Ps. aeruginosa* SP58, it was 25°C. However, the antimicrobial substance production levels at 25, 30, and 37°C were slightly different at $P<0.05$. This result might indicate that all antagonistic bacteria can be cultured and can produce inhibiting substances at a temperature range around room temperature. Temperature is one of the crucial factors in biological control due to the bioproducts requiring simple physical conditions for storage. The results of the optimized production are summarized in Table 2. It was found that the antibacterial activity rose when the bacterial cell growth increased. It has been noted that differences in the culture medium's composition may have an impact on both the yield of bacteria and the production of antibiotic substances.

Evaluation of antagonistic bacteria in the control of bacterial wilt under greenhouse conditions

The isolates *B. subtilis* SP15, *Ps. mosselii* SP38, and *Ps. mosselii* SP46 were selected for further evaluation based on the high capacity to inhibit the growth of pathogens in the agar test, the ability to produce siderophores and pheanzines, and that the species identification indicated that all selected strains were not harmful to other organisms. As *Pseudomonas aeruginosa* is recognized as a pathogenic microorgasim in humans, the isolate *Ps. aeruginosa* was not used for the *in vivo* test.

Greenhouse trial 1

In three trials, the effectiveness of the mixture of *B. subtilis* SP15, *Ps. mosselii* SP38, and *Ps. mosselii* SP46 to suppress pathumma wilt was assessed in greenhouse conditions. Despite the fact that the disease incidence of all the combinations was low, none of the antagonist mixed cultures provided total protection for the plants against wilt-causing bacteria. Pathumma plants treated with bacterial antagonists displayed a decrease in the pathogen's cells in the soil. The application of antagonists following inoculation with bacterial-wilt pathogens in the pathumma's rhizomes and soil in pots on the initial day of cultivation increased the health of the pathumma plants. The average disease incidence of the antagonists was 3.3% (Table 3). The viable cell number of antagonistic bacteria increased by 3% on average, while the pathogenic bacteria *Enterobacter asburiae* JK1, JK3, JK4, and *Enterobacter dissolvens* JK5 declined by 8, 32, 31, and 10%, respectively. When antagonists were co-applied with pathogens on shooting pseudostems and soil, the antagonists declined by 4.4% on average while the pathogenic bacteria JK1, JK3, JK4, and JK5 declined by 2, 32, 35, and 19%, respectively. Similar results were recorded when the pathogens were applied to cultivated pathumma plants, while the antagonists were introduced to the shooting pseudostems. The cell numbers of antagonists declined by 3% on average, while the pathogenic bacteria JK1, JK3, JK4, and JK5 declined by 38, 34, 38, and 54%, respectively. When the mixed cultures of antagonistic bacteria were only inoculated into the pathumma pots, it was found that the plants did not show wilt symptoms. The results of the disease incidence and the survival of antagonistic and pathogenic bacteria indicated that the mixed antagonists could suppress the growth of wilt-causing bacteria.

Greenhouse trial 2

The applications of the antagonistic bacteria for the control of wilt-pathogens were repeatedly evaluated. Most treatment experiments showed no wilt incidence, while the disease incidence for the control plants was 33-66%. After the antagonists and pathogenic bacteria were co-applied to pathumma rhizomes and soil before cultivation, the final cell concentration of antagonistic bacteria declined by 12.5% on average while the pathogenic bacteria *E. asburiae* JK1, JK2, JK3, and JK4 declined by 30, 15, 31, and 16%, respectively (Table 3). In experiment 2, when the antagonists and pathogenic bacteria were co-inoculated in pathumma pseudostems, the quantities of antagonists declined by 11% on average while the pathogenic bacteria JK1, JK2, JK3, and JK4

Table 3: Effect of antagonist mixture on wilt causing bacteria in pathumma plants when co-applied with antagonistic and pathogenic bacteria prior to cultivation (experiment 1) in 3 trials (year 1, 2 and 3)

Treatment	Trial 1			Trial 2			Trial 3		
	DI (%)	Bacterial population change (%)		DI (%)	Bacterial population change (%)		DI (%)	Bacterial population change (%)	
		Antagonists	Pathogens		Antagonists	Pathogens		Antagonists	Pathogens
Antagonists+JK1	13.3	10.1	-8.9[a]	6.7	-13.2	-30.4	6.7	2.8	-24.8
JK1	33.3	NC[b]	2.8	33.3	NC	-13.1	33.3	NC	-27.4
Antagonists+JK2	-	-	-	0	-12.2	-15.5	33.3	5.4	-23.8
JK2	-	-	-	33.3	NC	-12.0	33.3	NC	-26.9
Antagonists+JK3	0	-3.7	-32.2	0	-12.7	-31.2	0	2.5	-37.7
JK3	33.3	NC	-22.2	33.3	NC	1.1	33.3	NC	-26.9
Antagonists+JK4	0	-0.9	-31.1	0	-13.5	-16.4	0	3.6	-38.6
JK4	33.3	NC	-2.6	33.3	NC	-2.4	33.3	NC	-27.9
Antagonists+JK5	0	6.8	-10.9	-	-	-	-	-	-
JK5	66.7	NC	18.2	-	-	-	-	-	-
Antagonists+R227	-	-	-	-	-	-	0	2.8	-36.9
R227[c]	-	-	-	-	-	-	33.3	NC	-27.9

[a] - value displayed the decreased of cell number
[b] NC = No antagonist counting in the treatment
[c] R227 were standard *Ralstonia solanacearum* obtained from Ministry of Agriculture and Cooperatives, Thailand
- = not determined

declined by 24, 38, 40, and 35%, respectively. The treatment of antagonists in shooting plants after the inoculation of pathogens in rhizomes resulted in a bacterial reduction by 12% on average for the antagonists while the pathogenic bacteria JK1, JK2, JK3, and JK4 declined by 37, 24, 40, and 26%, respectively.

Greenhouse trial 3

When the mixed cultures of the antagonistic bacteria were introduced into pathumma rhizomes and soil in pots upon cultivation along with the pathogens, the plants showed slight wilt symptoms. The disease incidences of the antagonist treatments particularly in experiment 3 increased, compared to the previous studies in trial 1 and trial 2. The amounts of antagonistic bacteria increased by 3.4% on average, while the pathogenic bacteria *E. asburiae* JK1, JK2, JK3, JK4, and *Ralstonia solanacearum* R227 declined by 24, 23, 37, 38, and 37%, respectively, after 5 months of examination (Table 3). When the antagonistic bacteria were co-applied with the pathogens on the shoots of pathumma in pots, the amounts of antagonists declined by 9% on average while the pathogenic bacteria JK1, JK2, JK3, JK4, and R227 declined by 24, 23, 30, 39, and 28%, respectively. When the pathogens were applied to the cultivated pathumma, while the antagonistic bacteria were introduced to the shooting plants, the amounts of mixed antagonists declined by 9% on average, while the pathogenic bacteria JK1, JK2, JK3, JK4, and R227 declined by 24, 12, 24, 36, and 26%, respectively. The results of the wilt-causing bacterial growth inhibition in the greenhouse assay indicated that the antagonistic bacteria isolated from various soils were effective in controlling bacterial wilt caused by *Enterobacter* spp. Moreover, the results of all trials (trial 1, 2, and 3) showed that experiment 1 could highly reduce the amounts of pathogenic bacteria; therefore, this study agreed that the antagonists should be applied in the early cultivation of plants. Several reports have demonstrated that *Bacillus* and *Pseudomonas* could be suitable biocontrol agents against plant pathogenic bacteria. Jan *et al*., (2023) proposed that *Bacillus subtilis* FJ3 isolated from soil could suppress the number of plant pathogenic fungi. The crude extract of the antifungal substance inhibited *F. oxysporum*, *A. niger*, *A. flavus*, and *R.*

oryzae at 92%, 90%, 81.5%, and 56% cell reduction, respectively. Abo-Elyousr *et al*. (2022) demonstrated that *P. xanthii*, the causal agent of the powdery mildew of cucumber could be restricted by *B. licheniformis* and *B. aerius*. Vinayarani and Prakash (2018) stated that the treatment of *Bacillus* sp. and *Pseudomonas* sp. significantly increased the plant height and fresh rhizomes while decreasing the occurrences of rhizome rot and leaf blight diseases in turmeric under greenhouse conditions. In addition to *Bacillus* spp. and *Pseudomonas* spp., actinobacteria, i.e., *Streptomyces ramulosus*, *S. axinellae*, and *S. drozdowiczii*, exhibited the inhibition of wilt-causing bacteria including *X. oryzae*, *X. campestris*, and *R. solanacearum* (Promnuan *et al*., 2020). In the current study, applications of antagonists before or together with plant cultivation were suitable for disease prevention. The main problem of biological control was its low consistency and reliability under field conditions due to a high variability in efficacy. An *in vitro* experiment was restricted by the lack of a plant that could significantly affect the antagonist's capacity to survive, colonize, and inhibit pathogens, although being simpler to perform. When field trials occur, the *in vivo* test is more accurate in simulating the environmental conditions to which the antagonistic bacteria will be subjected. One of the realized variables for the evaluation of biological control was the inoculum. A co-inoculant was proposed to use with a favorable inocula due to the synergistic effect to enhance the biocontrol. This conclusion was supported by the possibility that using a variety of strains as a biocontrol agent could be beneficial by ensuring that at least one of the biocontrol mechanisms could function under the unpredictably changing ecological conditions that the released PGPR strains will encounter (Zhang *et al*., 2023). The antagonists should not be a risk to the environment. This study showed that *Ps. aeruginosa* could be beneficial to the plant but it is an opportunistic pathogen in humans and animals. Hence, it was suggested that this strain should be replaced by other organisms or used as an antimicrobial substance producer. Further studies should evaluate the biocontrol efficacy of antagonistic bacteria in the field, particularly with an earlier finding of the disease. In comparison to applying biocontrol agents in a greenhouse, applying them in the field is intrinsically more difficult and varied.

Designation of the mixed culture products

To select the most effective carrier, several media were tested for the maximum growth of antagonistic bacteria. The preliminary results revealed that molasses and soybean whey were the most efficient medium for bacterial growth. After secondary screening, it was found that molasses was the best liquid formulation product. This medium was further evaluated for the shelf-life of antagonistic bacteria for 90 days. The cell numbers of *B. subtilis* SP15, *Ps. mosselii* SP38, and *Ps. mosselii* SP46 increased by 1.4%, 1.2%, and 1.5%, respectively. Both soybean whey and molasses are waste products from industry. They are known to be a good fermentation medium, rich in protein, fat, carbohydrates, and fiber. However, the major problem of these carriers is that it is easy to contaminate with *Bacillus* and fungi, due to the high water activity. To evaluate the optimal carrier materials for antagonistic bacteria, three materials (soil, coir, and chaff) were examined for the survival in these carriers for 60 days. Soil was the most eligible carrier material for all antagonistic bacteria. It was interesting that the population changes of all the bacteria in coir were slightly different from the soil. All bacteria survived after incubation for 2 months (Fig. 2-4). The coir could replace the soil, since coir is an agricultural waste, and its cost is low. Dry formulation is one form of solid-state fermentation that has a low water activity (A_w) value. This formulation is considered advantageous over a liquid formulation in terms of the stability of potency with regard to storage and transportation costs. The dry formulation is lower in weight and does not require low temperature for long term storage (Barbosa-Cánovas *et al*., 2020). Due to their ability to produce a number of broad-spectrum antibiotics and their prolonged shelf life as a result of their ability to create endospores, *Bacillus* spp have been found to be beneficial in the biocontrol of numerous plant diseases (Promsai *et al*., 2023). Other researchers have reported a formulation of *Bacillus* and *Pseudomonas*. Abo-Elyousr *et al*. (2022) revealed that under greenhouse conditions, a cell suspension of *B. licheniformis* and *B. aerius* decreased the disease severity of powdery mildew and raised the fresh and dry weight of the plant in comparison to an untreated plant. Using talc-based formulations of *P. putida*, *B. cereus*, and *P. aeruginosa* as biocontrol agents inhibiting *P. aphanidermatum* and *R. solani*, which cause rhizome rot and leaf

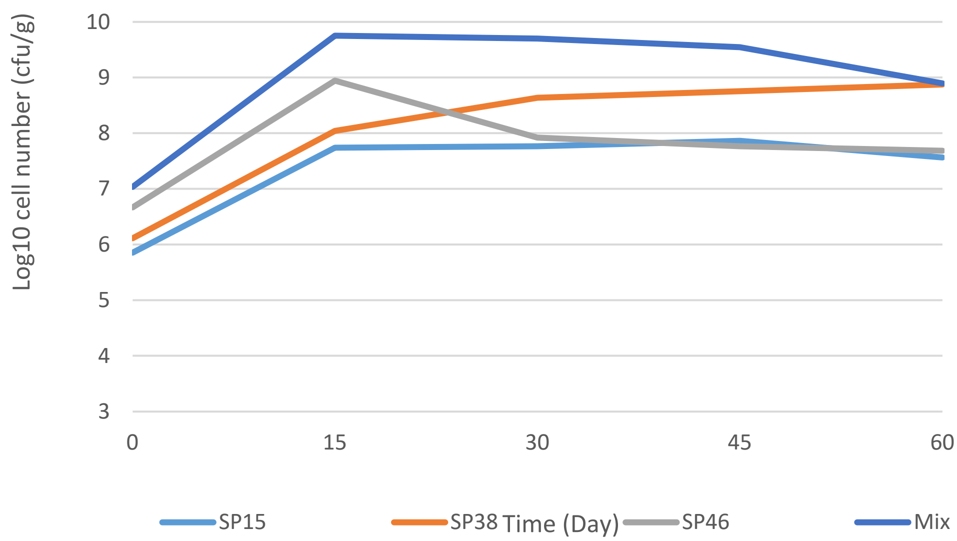

Fig. 2: Viable cell count of antagonistic bacteria in soil after incubation for 60 days at room temperature

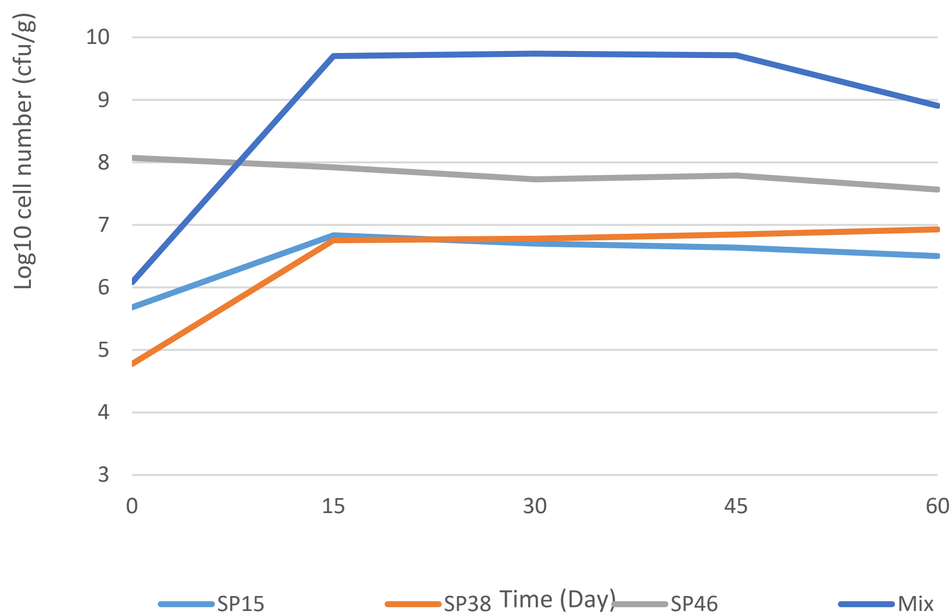

Fig. 3: Viable cell count of antagonistic bacteria in coir after incubation for 60 days at room temperature

blight diseases in turmeric, were administered to control these diseases. The results showed that the disease incidences were reduced after being treated with these formulations (Vinayarani and Prakash, 2018). A biological control agent (BCA)-based product's final efficacy is significantly influenced by its formulation, as well as by the processes of biomass discovery, manufacture, and stabilization. Even while numerous microorganisms have shown promise for their biocontrol capacity on a small scale, it is still extremely difficult to create biological control organisms that are effective. Effective formulation

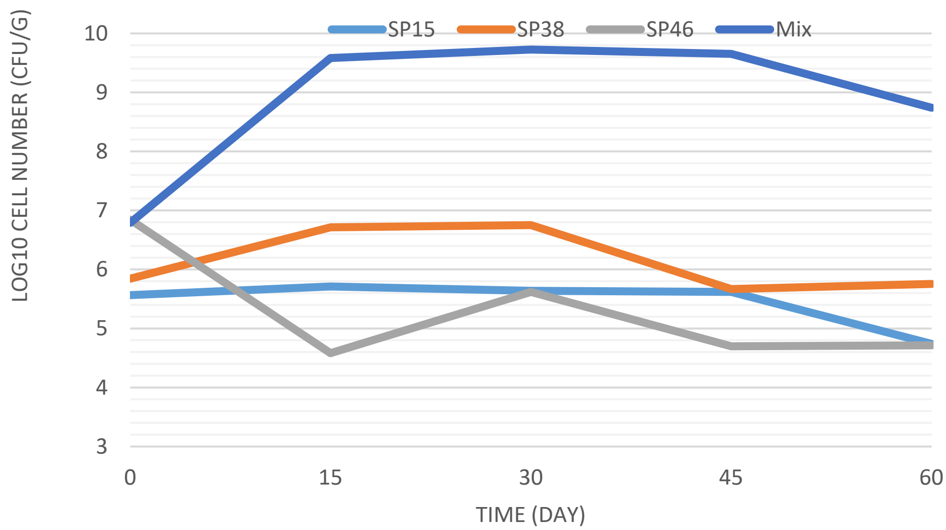

Fig. 4: Viable cell count of antagonistic bacteria in chaff after incubation for 60 days at room temperature

and successful organism scale-up are crucial for the steady and profitable development of pesticides (Ruanpanun and Nimnoi 2020). The development of an effective formulation strategy for BCAs depends on the choice of an acceptable carrier material. The carrier should help the biocontrol activity in the field survive and persist for a long time. The necessity for low cost, nonphytotoxic, and low visible residue from agriculture on saleable products must be considered in addition to the aforementioned factors (Abo-Elyousr *et al*., 2022). The formulation plays a significant role in determining the final efficacy of a BCA-based product, as do the processes of the discovery, production, and stabilization of the biomass. Although many microorganisms have exhibited promising biological control activity on a small scale, it remains a major challenge to successfully formulate biological control organisms. To develop a successful formulation protocol for biological control agents, selection of an appropriate carrier material is important.

CONCLUSION

An agar diffusion method was conducted to screen antagonistic bacteria for the biological control of wilt disease of pathumma. Among 105 bacterial isolates, four isolates, namely SP15, SP38, SP46, and SP58, which were *Bacillus subtilis*, *Pseudomonas mosselii*, *Pseudomonas mosselii*, and *Pseudomonas aeruginosa*, respectively, displayed the highest production of inhibiting substances. The optimal conditions of the inhibiting substance from the isolate SP15 was 30°C at pH 8 in modified TSB medium containing 0.5% (w/v) glucose and 2% (w/v) peptone SP38 was 25°C at pH 7 in modified TSB medium containing 0.5% (w/v) sucrose and 2% (w/v) peptone SP46 was 25°C at pH 7 in modified TSB medium containing 0.5% (w/v) glucose and 1.5% (w/v) peptone, and SP58 was 25°C at pH 7 in modified TSB medium containing 0.5% (w/v) sucrose and 1.5% (w/v) peptone. All antagonists could produce both hydroxamate-type and catecholate-type siderophores, and three strains including *Ps. mosselii* SP38, *Ps. mosselii* SP46, and *Ps. aeruginosa* SP58 showed the ability to produce phenazine derivatives. Wilt-disease reduction using antagonistic bacteria including *B. subtilis* SP15, *Ps. mosselii* SP38, and *Ps. mosselii* SP46 was assessed in a greenhouse study. It was found that the disease incidences of pathumma plants treated with antagonists decreased by 70-100%, and the amounts of pathogenic bacteria declined by 25-40% on average, while the number of the antagonistic combination generally decreased by 5–15%. This research revealed that the use of antagonistic bacterial strains should be applied before the pathogens were dispersed. The study of the designation of mixed-culture products identified that the dry formulation bioproduct for all antagonists was soil, respectively. It is expected that these antagonistic bacteria can be useful in wilt-disease management in agricultural fields in the future.

AUTHOR CONTRIBUTIONS

S. Promsai, the corresponding autor, contributed to original draft preparation, conceptualization, validation, compiled the data, review and editing manuscript. Y. Tragoolpua contributed to validation, review and editing manuscript. N. Thongwai contributed to supervising, validation, review and editing manuscript. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
µg	Microgram per milliliter
µL	Microliter
°C	Degrees Celsius
ANOVA	Analysis of variance
cm	Centimeter
cfu/g	colony forming unit per gram
cfu/mL	colony forming unit per milliliter
DI	disease incidence
g	Gram
Gagnep	Gagnepain
h	Hour
HCl	Hydrochloric acid
i.e.	Id est (that is)
min	Minute
mm	Millimeter
M	Molarity
nm	Nanometer
pH	Potential of hydrogen
TLC	Thin layer chromatography
TZC	Triphenyltetrazoliumchloride
TSA	Tryptic soy agar
TSB	Tryptic soy broth
v/v	Volume per volume
w/v	Weight per volume
xg	Gravitational force equivalent
ZOI	zone of inhibition

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SPECIAL ISSUE: Eco-friendly sustainable management
REVIEW PAPER

Environmental impact technology for life cycle assessment in municipal solid waste management

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ABSTRACT

Municipal solid waste management has evolved from direct disposal to recycling and resource recovery, driven by sustainability. Life cycle assessment has played a crucial role in analyzing the environmental implications of different waste management strategies and selecting the most ecologically feasible options. Establishing best practices in municipal solid waste management based on competent life cycle assessment work is essential for policymakers to make informed decisions. This study reviewed 34 life cycle assessment studies on solid waste management systems in Asian countries, examining their life cycle stages, assessment techniques, and key outcomes. The analysis highlights include functional units, various life cycle assessment models (such as SimaPro and GaBi), life cycle impact assessment methods, impact categories, and alternative waste management methods. It is necessary to prioritize recycling, resource generation (such as decomposition, incineration, and anaerobic digestion), and waste reduction over landfilling to attain a high level of environmental friendliness. However, it is essential to observe that technologies necessitating large upfront investments and skilled labor are better suited for high-income countries. Conversely, low-income countries should prioritize waste reduction through recycling, waste depots, and methods that correlate with their existing capabilities to reduce the amount of waste sent to landfills. By sharing existing methods, developing integrated municipal solid waste management systems can be accelerated in low-income nations, which can have a substantial positive economic impact. Therefore, decision-makers should consider social, economic, and environmental impacts when selecting an appropriate refuse management strategy for their nation. This analysis provides valuable insights into the scope of life cycle assessment studies and contributes to the selection of sustainable municipal solid waste management systems. These findings can be utilized by life cycle assessment practitioners, stakeholders, and Asian governments to inform policy development and decision-making processes.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
113	11	3

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INTRODUCTION

Municipal solid waste is a complex problem in many countries that impacts environmental quality and people's welfare (Charkhestani and Yousefi Kebria, 2022; Ghazali *et al.,* 2021; Zaman *et al.*, 2021). Previously, the quantity of waste production that is out of control, correlated with population growth, and its heterogeneous character has driven the shift from linear to circular economic management in waste management programs globally (Kurniawan *et al.,* 2022). The concept of sustainability is an approach that seeks to balance environmental, social, and economic aspects. In the context of municipal solid waste (MSW) generation, sustainability emphasizes the need to reduce waste generation, environmentally friendly management, and promote efficient production cycles (Bakan *et al.,* 2022; Weekes *et al.,* 2021; Kusumawati and Mangkoedihardjo, 2021; Puno *et al.,* 2021; Guerra Tamara *et al.,* 2022). Various studies show a relationship between MSW waste generation and sustainable concepts. Reducing waste generation can reduce the negative environmental impact and the need for expensive and limited landfills. Various steps such as reducing unnecessary and nondisposable packaging, reuse, and recycling, can reduce the amount of waste generated. Furthermore, environmentally friendly waste management is a key element of sustainable concept. Using technology for the types of waste to be processed such as sorting and composting organic waste, as well as applying efficient processing methods, can reduce the negative impact on the environment and produce alternative energy. To achieve a sustainable concept, involving stakeholders, such as government, private sector, civil society, and individuals, is crucial. Collaboration and cooperation between various parties are needed to develop effective policies, provide adequate infrastructure, and increase public awareness about the importance of managing waste sustainably. Asia is the world's largest continent and features rapid development. Based on a previous investigation, the urbanization rate of the typical Asian population is 3 – 4 percent (%) annually (Bren d'Amour *et al.,* 2017). Population expansion affects numerous vital aspects, including food consumption demand, economic development, urbanization, and industrialization, affecting the formation of MSW in Asian nations (Nanda and Berruti, 2021). The average MSW output in Asian countries is 4.4 109 tons per year (t/y) (Pappu *et al.,* 2011) and costs ~25 million United States Dollars annually for MSW management (Alam *et al.,* 2022), as Illustrated in Fig. 1 (Hoornweg *et al.,* 2012). Countries with a high per capita income and gross domestic product (GDP) and countries with a low GDP create more packaging waste (plastic and paper) than those with a high GDP (EPA, 2010). Meanwhile, nations with a low GDP produce more biodegradable waste (Aleluia and Ferrão, 2016).

For policymakers to determine their optimal method, it is critical to establish the best and most efficient practices for MSW management with competent life cycle assessment (LCA) methods (Iqbal *et al.,* 2020). The results of the critical evaluation are based on the LCA study with reference to the international standards used. Due to various conditions that must be met, such as technological, economic, social, and geographical. It is difficult to draw conclusions or make generalizations about the optimal technology or strategy for MSW management based on the existing conditions in each country. However, if the review's scope is broad enough to include several low- to high-income nations, the findings may offer crucial information and highlight the best approaches to adopt for long-term MSW management for general policymakers. Numerous studies use LCA to analyze MSW management, and most of these studies have three primary goals: i) to evaluate the environmental performance of particular technologies; ii) to contrast various waste treatment options; and iii) to offer useful modifications of current treatment processes to reduce associated environmental impacts (Rizwan *et al.,* 2019). Even among studies pursuing the same goal, LCA outcomes can differ due to differences in local circumstances, data sources (Steubing and de Koning, 2021), the subjective implications of various researchers, and other contributing factors. MSW management, lacking scientific rigor, may impose remarkable environmental consequences, including climate change, ecological degradation, and the depletion of natural resources (air, water, and soil) (Manna *et al.,* 2018). LCA is a method for determining the most environmentally, economically, and socially sustainable strategy for managing MSW (social LCA) (Zarea *et al.,* 2019). The LCA methodology can be used to analyze the potential environmental impacts of cradle-to-grave limits (from the extraction of raw materials to manufacturing, usage, and disposal), cradle-to-gate (extraction of raw resources to factories for production), and

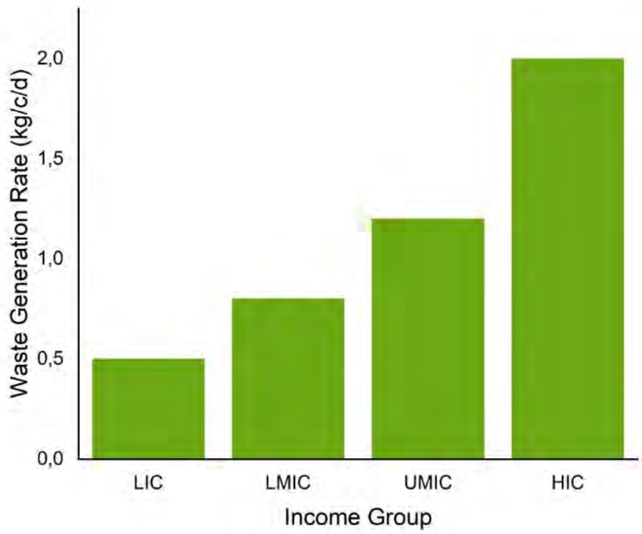

Fig. 1: Municipal solid waste generation rate in countries with different income groups (Hoornweg *et al.,* 2012)
(LICs-low-income countries, LMICs-lower middle-income countries, UMICs-upper middle-income countries, HICs-higher income countries)

gate-to-gate (reception of materials by factories to transport items created to the gate) methods, based on the requirements of each study (Abd Rashid and Yusoff, 2015). The author conducted a study on MSW management in Europe. Table 1 shows that most review studies examined certain forms of solid waste, such as paper, cardboard, plastic, biowaste, and organic waste; however, only a few studies have included all MSW management options. Table 1 shows the number of published review articles that solely discuss the LCA approach for MSW management in Europe; moreover, no research has addressed LCA in MSW management for the Asian continent. Herein, several Asian-authored scientific works on LCA for MSW management that have appeared in recent peer-reviewed journals have been critically analyzed. This study aims to achieve two goals: to evaluate best practices in MSW management with sustainable principles and to summarize systematic ideas with LCA methods for high-quality management of MSW. The results of this review can form the basis of agreement among researchers to increase the use of LCA for their practitioners in selecting methods. They will also offer indepth recommendations for better MSW management practices for adoption by policymakers worldwide based on technological, environmental, and socioeconomic factors. Table 1 shows the published review on the LCA of MSW in European countries.

METHODOLOGY

This study focused on LCA studies on MSW management involving waste generation from households, educational institutions, and industries. Using SCOPUS and Google Scholar and the keywords "life cycle evaluation of municipal solid waste management," publications for 35 LCA studies on MSW management systems since 2013 were obtained. The processing grouping is divided into two in Tables 2 and 3. MSW management is centralized with one management method analyzed and integrated with several combinations of management, aiming to compare the most efficient methods in the management of MSW. Data were collected and analyzed using a qualitative content analysis approach, which provides an understanding of the phenomena studied and allows flexibility in analysis through visual and verbal data collection. To create an adequate assessment database regarding the environmental impact of processing MSW through LCA, the authors searched the SCOPUS database using the operator "TI-TLE-ABS-KEY (MSW and Life cycle assessment and Asian)." The studies were examined based on the following: i) the study area and the history of LCA research in the region, ii) the functional unit, iii) the system boundary and application of the LCA model, iv) sensitivity analysis, v) environmental impact categories, vi) comparisons of potential waste

Table 1: LCA municipal solid waste study in Europe

Country	Objectives of the research	References	Remarks
Croatia	Considering waste management methods in landfills to be more developed because there is no other waste management that can reduce the volume.	Hadzic *et al.* (2018)	All previously published literature reviews regarding LCA implementation in MSW management are comprehensive. Although research is limited to specific solid waste components such as paper waste, cardboard garbage, plastic waste, bio waste, and organic waste, few studies evaluate MSWM in general. Most published review articles focus on the methodology of LCA studies. Previously, LCA studies on MSW management in the entire Asian continent have not been assessed.
United Kingdom	Provides towns with a standard for operating their MSW management .	Albores *et al.* (2016)	
Scotland	Examines the evolution of LCA study methodology and the distinctions between attributional and consequential LCA methodologies.	Brander (2017)	
Central European	The findings of life cycle evaluations indicate that plastics recycling is preferable to the alternatives evaluated in this study (i.e., municipal solid waste incineration and manufacturing of virgin plastics) from both environmental and economic perspectives.	Wäger and Hischier (2015)	
United Kingdom	Provides an overview of current LCA models applicable to solid waste management (SWM).	Robert *et al.* (2018)	
Italy	Examines LCA studies of biowaste treatments, including anaerobic digestion.	Cecchi and Cavinato (2015)	
Canada	Findings show that 82 LCA studies address the management of organic wastes.	Morris *et al.* (2013)	
Germany, Denmark, France, United Kingdom, Greece, Poland, Italy	Examines the environmental effect of LCA based on studies completed in seven European countries.	Bassi *et al.* (2017)	

management strategies, and vii) the gaps and the most important findings. Conference reviews lacked the necessary peer review to be deemed a reliable source of information because they were not subject to the same standards as journal articles; viii) Old publication date: as more recent research has been done, conference reviews written before 2013–2023 may be considered outdated. The authors conducted a thorough study analysis after reading the title, citation information, abstract, keywords, and entire text to attain credibility, reliability, and believability Fig. 2.

Tables 2 and 3 summarize the MSW management methods found in all Asian countries. Each article analyzed has its own characteristics, such as the method used, the environmental impacts that occur, and the LCA model used. The functional unit of each research analyzed summarizes the red lines of the results obtained to know the management efficiency in a nutshell; all of these will be discussed in the next section. The MSW categorization adopted from various selected studies includes waste originating from cities, and various household activities, including biodegradable, construction, electronic, and composite waste (such as clothing to medical waste).

Review scheme

Critical reviews focus on the fundamental components of LCA for MSW management, such as the definition of objectives and scope, functional units, assumptions, choice of effect categories, and critical parameters/factors. These components were discovered through several LCA studies in Asia. After categorizing the research according to their unique traits and the treatment techniques used, a logical ranking of the best technology/policy was created. Recommendations and implications for optimal MSW management practices are provided based on various technological, environmental, and socioeconomic considerations.

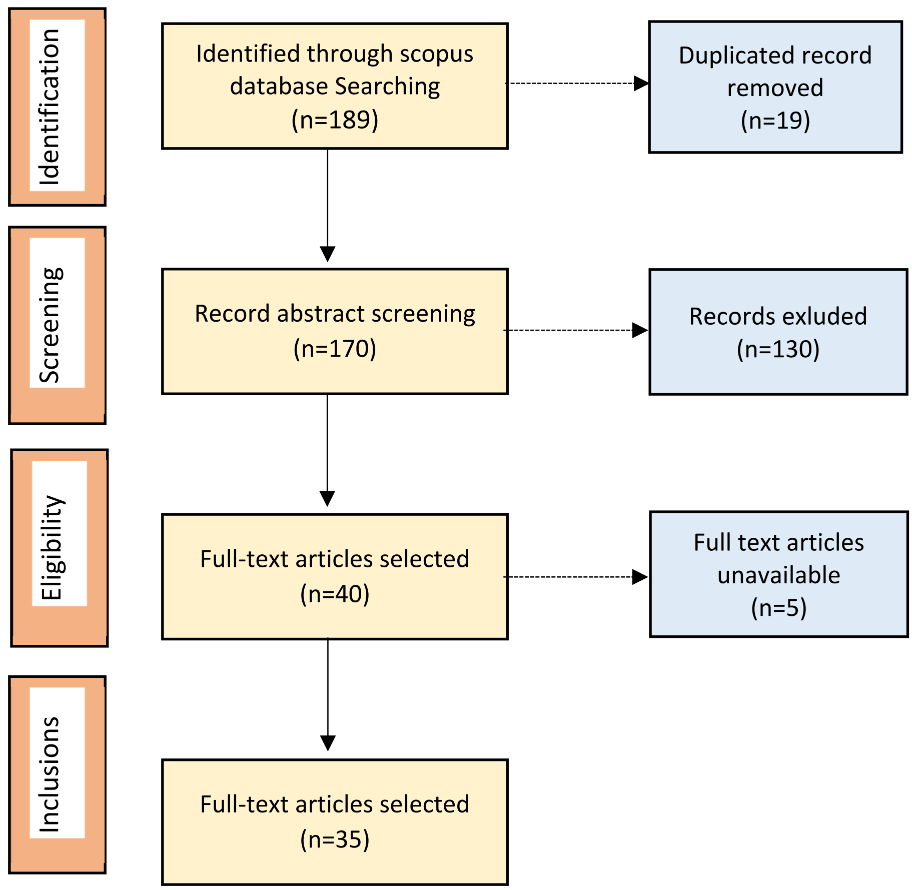

Fig. 2: Literature review method

Mapping of the study area and evolution of LCA studies in Asia

Fourteen Asian countries were identified for LCA, among which China is the largest. Fig. 3 shows the distribution of LCA studies (indicated in parentheses) selected for evaluation 1, i.e., China (11), Iran (4), India (4), Thailand (3), Turkey (2), UAE (2), and nine other countries with the same value, namely Japan (1), Lebanon (1), Indonesia (2), Qatar (1), Riyadh (1), Tehran (1), Vietnam (1), Hong Kong (1), Philippines (1). China (10) has conducted significant research in this field owing to its larger national population. Based on (Zhou *et al.,* 2014), China promptly identified and adapted to sustainable MSW management processing using LCA based on increased incineration plants in China. In 2003, there were 47 incineration plants in China, which increased to 138 in 2012.

The most LCAs were seen in 2022, while the fewest LCAs were observed in 2013, 2016, 2018, and 2021, all of which had the same amount of LCAs. The number of LCAs increased in 2013 and 2015 then decreased and remained constant from 2016 to 2018. The number of LCAs increased in 2019 and 2022, as shown in Fig. 4. No specific explanation is available for the large or small number of LCAs in any year. According to (Yadav and Samadder, 2018), fluctuations in the LCA can be attributed to issues related to waste in certain years, the level of activity within the scientific community, and the availability of functional units for MSW management-related projects. This trend in the LCA reflects the significance of using LCA to assess the environmental impacts of MSW management. Increasing adoption of LCA studies correlates with the increasing adoption of ISO 14044:2006 standards

Table 2: Excerpts from an LCA study on centralized management of MSW in Asian countries

Study location	Functional unit (FU) model and method	Scenario	Impact assessment result of parameter	Critical findings	Sources
China	FU: 1 Ton MSW Model: GaBi Method: CML 2001	S1: INC S2: Co- INC with MSW S3: Co- INC with coal S4: Co- INC in cement kiln	1. GWP 2. AP 3. EP 4. ADP 5. MAE 6. HTP	*Single incineration* is the approach that can potentially have the most damaging effects on the environment, including climate change, eutrophication, abiotic depletion, and marine ecotoxicity, when compared to the three other options for joint incineration.	Xiao *et al.* (2022)
Japan	FU: 1 Ton MSW Model: IWM2 Method: IPCC	S1: ODL S2: SLF S3: MBCS S4: KRS	1. GWP	Anyama's waste management system contributes to a rise in overall emissions. Cote d'Ivoire's solid waste management systems are not intended to create an integrated management system.	Kouassi *et al.* (2022)
Iran	FU: 1 Ton MSW Model: GaBi Method: NS	S1: COMP S2: AD S3: INC S4: MRF S5: ATT S6: LFG	1. VOC 2. SO_2 3. CO_2 4. NO_X	The model also suggests that MRFs, Incinerators, Composting, and LFGRS are the optimal facilities for managing municipal solid waste in Mazandaran's province. The study was bolstered by a cost–benefit analysis as well.	Harijani and Mansour (2022)
China	FU: 1982 Mt MSW Model: SimaPro Method: CML-IA	S1: INC: LF = 2:7 S2: INC: LF = 11:6 S3: INC: LF = 5:1 S4: INC: LF = 5:1 CO_2 Capture System	1. GWP 2. ODP 3. HTP 4. POCP 5. AP 6. EP	Increased energy recovery by producing power from incineration will be crucial to functional environmental advantages.	Liu *et al.* (2020)
China	FU: 1ton MSW Model: NS Method: NS	S1: INC S2: WWTP S3: LF S4: COMP	1. GWP	S3 was found to have the highest environmental impacts, even producing electricity.	Chen *et al.* (2020)
China	FU: 1ton MSW Model: NS Method: CML-IA	S1: WTE S2: AcRR	1. GWP 2. AD 3. POS 4. EP 5. HTP	AcRR has the most significant advantage, but some things that could be improved in the actual promotion process, reflected notably by the lack of governmental backing.	Liang *et al.* (2022)
India	FU: 1ton MSW Model: NS Method: NS	S1: ODL S2: LF, WTE S3: LF, WTE S4: BLF system	1. GWP 2. AP 3. EP 4. POCP	The bioreactor landfill option is the most advantageous of the four situations.	Sivakumar Babu *et al.* (2017)
Lebanon	FU: 1 Ton MSW Model: ESATECH Method: ILCD	S1: LF, with flaring S2: LF, Energy recovery S3: MRF (15%), COMP (50%), LF (35%) flaring S4: RCYCL (15%), AD (50%) with energy recovery, LF (35%) with flaring S5: INC (100%) energy recovery	1. GWP 2. SOD 3. FE 4. MAE 5. DAR 6. POF 7. AP	Under scenarios emphasizing recycling and composting, environmental advantages may be realized, with cost savings on emissions reaching up to 98%.	Maalouf and El-Fadel (2019)

Continued Table 2: Excerpts from an LCA study on centralized management of MSW in Asian countries

Study location	Functional unit (FU) model and method	Scenario	Impact assessment result of parameter	Critical findings	Sources
Indonesia	FU: 1kg MSW Model: Open LCA Method: CML	S1: ODL S2: INC S3: RDF	1. GWP 2. EP 3. AD 4. HT 5. ODP 6. Economy	From the three waste processing scenarios at the Cirebon cement factory, Fluff RDF is more ecologically favorable than open dumping and incineration.	Anasstasia *et al.* (2020)
Qatar	FU: 1kg MSW Model: GaBi Method: Recipe 2016	S1: LF S2: Biogas Capture from LF S3: Biogas capture and SRF gasification. S4: Biogas capture and SRF gasification with solar technology.	1. GWP 2. TE 3. MAE 4. WD 5. FD	The findings suggested that Scenario 2 reduces climate change significantly at a lesser cost than the other scenarios.	Al-Moftah *et al.* (2021)
Riyadh	FU: 1ton MSW Model: SimaPro Method: Recipe 2016	S1: LF S2: DWR S3: OWM S4: RWM	1. GWP 2. TE 3. FE 4. MRS	It has been shown that garbage recycling and waste-to-energy MSW treatments are essential for managing waste disposal difficulties and lowering the GHG emissions resulting from MSW management.	Aldhafeeri and Alhazmi (2022)
Tehran	FU: 1ton MSW Model: NS Method: NS	S1: COMP S2: RECYL S3: LF	1. GWP 2. EP 3. HT	Compared to the first scenario, the second and third scenarios lowered emissions by 64% and 72% during the second phase.	Rahimi *et al.* (2019)
Thailand	FU: 1ton MSW Model: NS Method: NS	S1: LF, WtE S2: INC	1. GWP 2. Economy	Better design (e.g., initiating LFG recovery into energy during the active phase of a landfill, using appropriate technology to extract LFG, and maximizing energy utilization by cogeneration of heat and power to be used to generate revenue).	Menikpura *et al.* (2013)
Turkey	FU: 1ton MSW Model: SimaPro Method: CML-IA	S1: Waste Separate S2: PW was not separated into 2 fractions S3: WS into 3 fractions S4: WS into 4 fractions. S5: WS 2 fractions as mixed packaging waste and glass waste. S6: WS into 3 fractions S7: WS in 2 fractions S8: WS into 3 fractions.	1. AD 2. AP 3. GWP 4. ODP 5. HT 6. PO 7. EP	According to this analysis, none of the alternative scenarios outperformed the present system. However, an ecologically superior outcome may be achieved by considerably altering the underlying assumptions, such as participation rate or material type.	Yıldız-Geyhan *et al.* (2016)
UAE	FU: 1ton MSW Model: SimaPro Method: CML-2001	S1: INC S2: GS S3: AD S4: COMP S5: BLF	1. AD 2. AP 3. EP 4. ODP 5. HT 6. MAE	Composting is the least environmentally friendly option in terms of the likelihood of creating no byproducts that may be utilized to generate electricity or replace nutrient-rich	Arafat *et al.* (2015)

Continued Table 2: Excerpts from an LCA study on centralized management of MSW in Asian countries

Study location	Functional unit (FU) model and method	Scenario	Impact assessment result of parameter	Critical findings	Sources
			7. TE 8. PO	fertilizers. However, if used in agriculture, it is beneficial.	
Vietnam	FU: 11,448-ton Mixed waste Model: NS Method: NS	S1: AL S2: SAL S3: LF Gas Capture S4: COMP S5: PC S6: Biogas Production	1. GW P 2. Eco nomy	Landfills emit more greenhouse gases than composting and biogas generation. This is primarily due to the production and release of methane during biological decomposition in landfills.	Othman *et al.* (2013)
China	FU: 1 ton FW Model: SimaPro Method: CML 2001	S1: BBR S2: AD S3: Digestate	1. GW P 2. AP 3. EP 4. FAE TP 5. HT	Identified the central pretreatment system (containing pretreatment and AD) as the most effective system on Economy Consumption and Environmental Impact.	Jin *et al.* (2015)
HongKong	FU: 1 ton FW Model: NS Method: NS	S1: LF S2: INC	1. GW P 2. Eco nomy	AIF has a higher economic value than LFE when external expenses are considered.	Woon and Lo (2016)
China	FU: 1 ton FW Model: GaBi Method: EDIP 97	S1: LF S2: LFGTE S3: INC with WTE	1. GW P 2. AP 3. NE 4. POF 5. HT 6. ETw c	All environmental consequences diminish substantially once the gas is gathered and processed (scenario 1). Incineration (scenario 2) is superior to landfill except for problems connected to toxicity.	Dong *et al.* (2013)
China	FU: 1ton Volatile Solid (VS) Model: GaBi Method: Recipe	S1: AD for FW and Sludge S2: AD of FW S3: FW to Landfill	1. GW P 2. ODP 3. HTP 4. PO 5. TE 6. MAE 7. TE 8. MAE 9. WD	The findings suggested that the most acceptable environmental scenario for treating FW during its whole life cycle was S-2 (i.e., AD of FW).	Xu *et al.* (2015)
China	FU: 1 ton MSW Model: EASEWASTE Method: Recipe	S1: INC	1. GW P 2. AP 3. OD 4. NE 5. POC P 6. HTs 7. ECw c 8. ECs 9. HTw 10. HTa	In addition, potential improvement procedures for burning mixed, unclassified MSW were developed, resulting in excellent environmental performance.	Lou *et al.* (2015)
Iran	FU: 1 ton MSW Model: SimaPro Method: CML 2 baseline 2000	S1: INC S2: LF	1. AD 2. AP 3. EP 4. GW P 5. ODP 6. HT	The findings of a life cycle analysis reveal that incineration reduces the toxicity-related impacts of power generation and phosphate fertilizer production.	Nabavi-Pelesaraei *et al.* (2017)

Continued Table 2: Excerpts from an LCA study on centralized management of MSW in Asian countries

Study location	Functional unit (FU) model and method	Scenario	Impact assessment result of parameter	Critical findings	Sources
			7. FAE TP 8. MAE 9. TE 10. PO		
China	FU: 1 ton Model: Gabi Method: CML-IA 2000	S1: AD S2: INC WtE S3: CROESB S4: DDFD	1. AD 2. AP 3. EP 4. GW P 5. HT 6. MAE 7. PO 8. TE	Inorganic waste is treated using carbothermal reduction, and oxygen-enriched side blowing; organic waste is treated using demulsification depolymerization and directional flocculation; and kitchen waste is treated using anaerobic digestion. Household waste is also burned to produce electricity.	Chen *et al.* (2023)
India	FU: 1 ton Model: Gabi Method: Recipe	S1: GS S2: SA	1. AD 2. AP 3. GW P 4. PO	According to this comparative analysis, the foundations of alternative sorbent production seem to depend on the chosen production method rather than the material itself.	Výtisk *et al.* (2023)
Indonesia	FU: 1 ton Model: Simapro Method: CML-IA	S1: SF S2: OF	1. AD 2. AP 3. FEP 4. GW P	According to the sensitivity analysis, the main factors influencing the variance in GHG emission per ton of product were yield and the usage of organic fertilizers. As a result, it is advised that Indonesia's fertilizer recommendation system incorporate the usage of organic fertilizer.	Kashyap *et al.* (2023)
Thailand	FU: 1 ton Model: Simapro Method: Impact world+	S1: INC S2: COMP S3: LF	1. GW P 2. TE 3. PO 4. MAE 5. FE	For instance, photochemical oxidant production, which was inversely correlated with the amount of waste or distance reduced, can be lessened by onsite systems.	Rotthong *et al.* (2022)

S1, S2, S3, S4, S5, S6, S7, S8: Represents scenarios selected in respective investigations

for LCA methodologies worldwide (Khandelwal *et al.,* 2019). According to (Laurent *et al.,* 2014b), research, policy initiatives, and implementation of ISO standards have increased LCA implementation. The focus of critical reviews is the fundamental components of LCA for MSW management, such as the definition of objectives and scope, functional units, assumptions, choice of effect categories, and critical parameters/factors. These components were discovered through several LCA studies in Asia. After categorizing the research according to their unique traits and treatment techniques, a logical ranking of the best technology/policy was created. Recommendations and implications for optimal MSW management practices are provided based on various technological, environmental, and socioeconomic considerations.

Scope definition

This section analyzes the essential parts of the results obtained, including functional unit, system boundary and model use, impact category, and

Table 3: Excerpts from an LCA study on management of MSW combinations in Asian countries

Study location	Functional unit (FU) model and method	Scenario	Impact assessment result of parameter	Critical findings	Sources
China	FU: 1ton MSW Model: NS Method: NS	S1: MRF, COMP S2: INC with energy recovery S3: LF S4: RDF + INC Energy Recovery	1. GW P	Sustainable MSW management requires public education. Building accessible, supporting facilities and giving waste separation information might promote public participation in separate collections.	Wang *et al.* (2022)
China	FU: 1ton MSW Model: SimaPro Method: EPD	S1: INC S2: Mono- INC SS S3:Superimposed MSW and SS INC S4: Integrated INC of MSW and SS system	1. GW P 2. ODP 3. TET	S1 and S4 have the smallest edge of the other scenarios because implemented circular economy produces electricity.	Chen *et al.* (2019)
Thailand	FU: 1ton MSW Model: SimaPro Method: Recipe	S1: CLL, SRT+ RCYCL + ACL+LNF S2: CLL, SRT + LNF S3: LF+ RDF + RCYCL	1. GW P 2. TE 3. FAE TP 4. HT 5. POF 6. PMF 7. FD	S1 landfilling had the greatest environmental effect, whereas S3 had the least environmental impact since no waste was disposed of in landfills, and RDF was introduced.	(Sukma *et al.* (2022)
Iran	FU: 292.000ton MSW Model: NS Method: NS	S1: LF, WTE S2: LF, WTE S3: COMP and LF without biogas collection; S4: RCYCL and COMP S5: COMP and INC; S6: AD, RCYCL, and LF; S7: AD and INC	1. GW P 2. AP 3. PO 4. ECT	Scenarios 6 and 7 thermal treatment and anaerobic digestion produced the most photochemical oxidants owing to significant pollution emissions.	Zarea *et al.* (2019)
India	FU: 1 Mt MSW Model: GaBi Method: CML-IA	S1: COMP & LF S2: MRF, COMP, LF S3: MRF, AD, LF S4: MRF, COMP, AD, LF	1. GW P 2. AP 3. EP 4. ADP 5. HTP 6. POC P	Analysis showed that MRF would boost environmental benefits since recycling rates lower environmental load.	Khandelwal *et al.* (2019)
India	FU: 1 Mt MSW Model: GaBi Method: IPCC	S1: ODL, BLF S2: MRF, SLF S3: MRF, COMP, SLF S4: MRF, AD, SLF S5: MRF, COMP, AD, SLF S6: MRF, COMP, INC S7: MRF, INC	1. GW P 2. EP 3. AP 4. HTP	Due to their greater energy output, incineration-based scenarios escape the most responsibilities.	Sharma and Chandel (2017)
Lebanon	FU: 1 Ton MSW Model: ESATECH Method: ILCD	S1: LF, with flaring S2: LF, Energy recovery S3: MRF (15%), COMP (50%), LF (35%) flaring S4: RCYCL (15%), AD (50%) with energy recovery, LF (35%) with flaring S5: INC (100%) energy recovery	1. GWP 2. SOD 3. FE 4. MAE 5. DAR 6. POF 7. AP	Under scenarios emphasizing recycling and composting, environmental advantages may be realized, with cost savings on emissions reaching up to 98%.	Maalouf and El-Fadel (2019)

Continued Table 3: Excerpts from an LCA study on management of MSW combinations in Asian countries

Study location	Functional unit (FU) model and method	Scenario	Impact assessment result of parameter	Critical findings	Sources
Turkey	FU: 1ton MSW Model: SimaPro Method: CML-IA	S1: LF S2: MRF, LF S3: MRF, COMP, LF S4: INC, LF S5: MRF, COMP, INC, LF	1. AD 2. GWP 3. OD 4. HTP 5. MAE 6. TE 7. PO 8. AP 9. EP	Alternative 5 is the finest choice with the most environmental advantages. Still, it may need to be more economically viable soon due to its high investment and operating expenses. Consequently, Alternative 3 may also be a viable choice.	Yay (2015)
Philipines	FU: 1ton MSW Model: NS Method: NS	S1: COMP, RCYCL, ODL, CDS, SLF, SD, OD S2: COMP, RCYCL, ODL, SLF, SD, OB S3: COMP, RCYCL, CDS SLF, SD, OB	1. GWP	Open burning of uncollected rubbish accounts for 1,628 tons of yearly emissions in British Columbia, based on business-as-usual operations.	Premakumara *et al.* (2018)

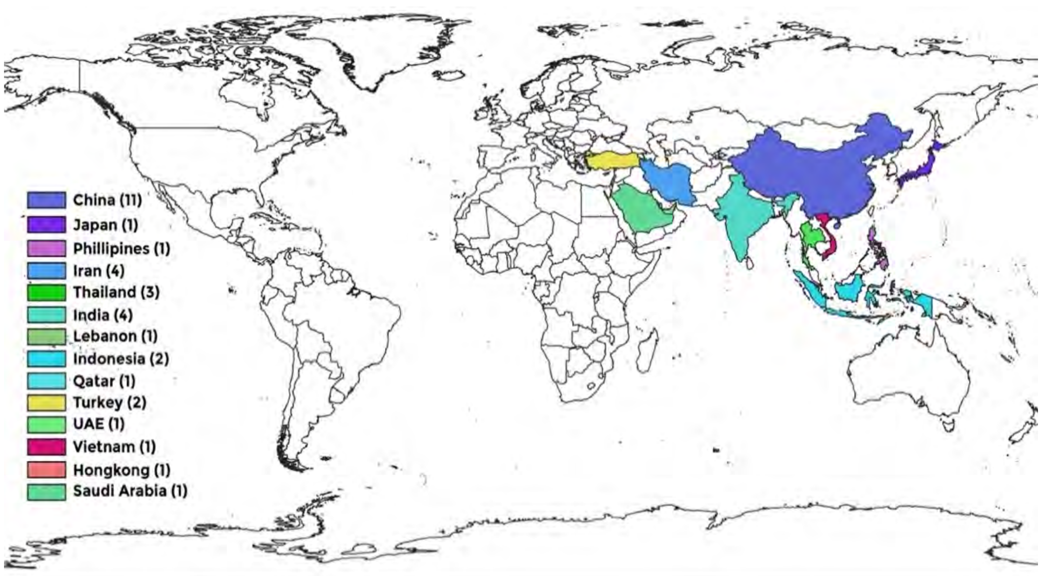

Fig. 3: Geographical distribution of selected LCA studies

sensitive parameters. These will be analyzed in more detail in the following sections.

Functional unit

The LCA approach focuses on a functional unit as the fundamental reference point. The measurable performance of the production system used as a reference unit related to the output outcomes is known as the available unit. A comparative LCA conducted using the evaluated system must provide the same functional unit; the waste capacity must be proportional to the same basis. Generally, the functional unit is the baseline for comparing analytical data (ISO14040, 2006). The often used FU in LCA research is reviewed based on the total mass or unit mass of waste, such as annual MSW generation, or

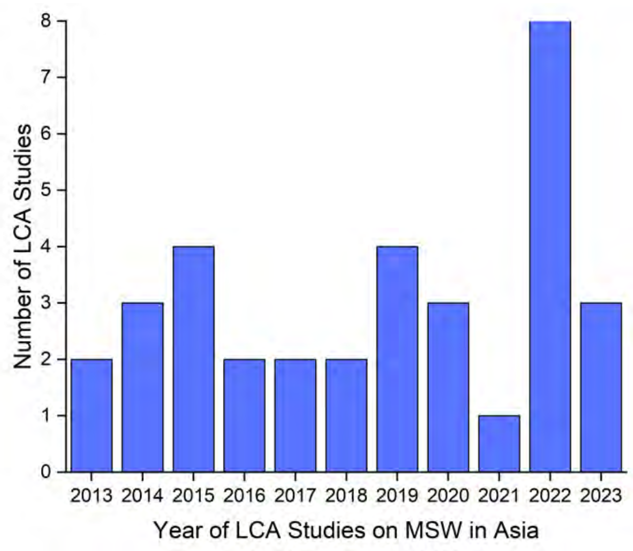

Fig. 4: Time evolution of LCA studies (2013-2023)

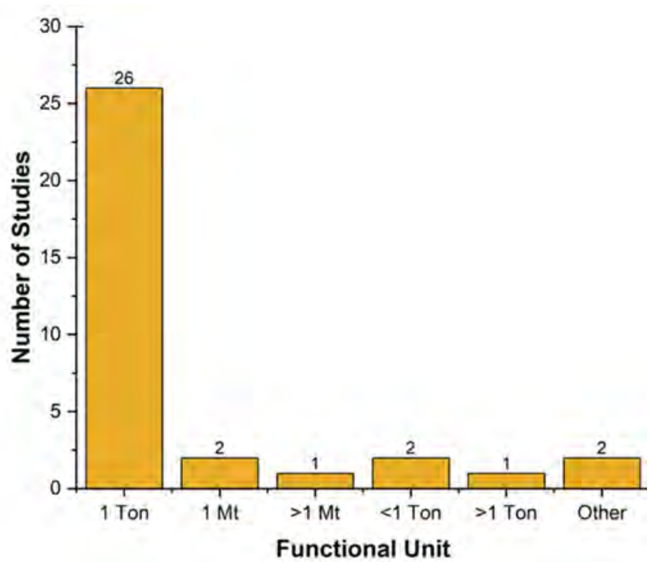

Fig. 5: Distribution of studies on functional units used.

1 t and 1 Mt generates MSW (Kaszycki *et al.*, 2021). Limiting the overall amount of garbage as FU can give a general understanding of the waste management issue today and what needs to be managed in the future to improve local waste management from an economic and environmental standpoint. The functional unit of MSW is the quantity of waste processed in the study. Fig. 5 shows the functional units obtained from the LCA experiments reported herein. The most typical functional unit was one ton of MSW (19 among 31 studies). By contrast, two studies used 1 Mt, two used 1 ton, and two used >1 Mt. Six studies on food waste (FW), volatile solids, and sludge used functional units other than MSW. The functional units were selected based on the aim and scope of the investigation. (Alhazmi *et al.,* 2021)

stated that the credibility of an LCA study relies on the definition of its aims and scope, as well as the proven functional unit. In contrast, undefined functional units result in erroneous conclusions.

System boundary and use of the LCA method

System constraints, also known as "analytical constraints," are very crucial for the initial part of the LCA method. According to Yadav and Samadder (2018), the system limit of the LCA is vital and significantly affects the overall outcome. It is defined as a processing unit that includes the operation phases, input, and output, as well as the operating time of the SWM option (Othman *et al.,* 2013). The system boundary determines the inclusion or exclusion of unit processes or variable components from the study, significantly affecting the evaluation findings (Iqbal *et al.,* 2020). The system boundaries must consider the study's duration, scope, and purpose of the study, and decisions to exclude processes or inputs/outputs must be explained (Standardization, 2006). The system constraints must ensure that all relevant processes and their possible environmental implications are considered in the evaluation. A precise system boundary definition mitigates the risk of load shifting from one phase of the life cycle to another (Laurent *et al.,* 2014a).

A model is a computer-based tool for collecting, organizing, and analyzing data; simulating waste management systems; and evaluating emissions and their environmental effects (Khandelwal *et al.,* 2019). Although conducting an LCA does not require the use of modeling software, it can help acquire, organize, and analyze inventories. Software typically for LCA, such as SimaPro and GaBi, can be used for the LCA of any product or service. The researchers chose SimaPro and GaBi for environmental impact analysis because they have various tools for characterizing and evaluating environmental impacts that can be used to examine MSW. They also have databases for raw materials, energy, and waste, allowing for the modeling and analysis of MSW throughout its life cycle (Iswara *et al.,* 2020). Other software developed specifically for LCA waste management, such as the Environmental Assessment of Solid Waste Systems and Technologies (EASEWASTE), has been superseded by a wide variety of other systems, such as the Environmental Assessment System for Environmental Technologies (EASETECH), integrated waste management, and opens LCA (Cleary, 2009). LCA analysis software is used to assess the environmental effects of solid waste management (SWM) systems. LCA entails thorough data collection on all MSW management phases, including producing raw materials, waste processing, transportation, and disposal. The general LCA analysis steps are i) Goal and scope determination: the program user chooses the analysis's goals and establishes the SWM system's evaluation's review's confines. ii) Lifecycle inventory: data pertaining to input and output are gathered and input into the software. This includes details about the quantity and kind of raw materials utilized, the amount of energy used, emissions, and other details from each process. iii) Characterization of environmental impact: the information gathered is utilized to describe how each stage of the SWM system affects the environment. (iv) Results interpretation: the results of the LCA study are evaluated to understand the relative contributions of each stage of the SWM system to the overall environmental impact. Fig. 6 shows the amount of software used in the analyzed studies. Approximately 69% of the studies used the LCA technique to simplify MSW management systems and considered the environmental benefits and costs. SimaPro was used in 28% of the studies, followed by GaBi and ESATECH, with utilization rates of approximately 25% and 6.3%, respectively. Three studies used the IWM2, EASEWASTE, and open LCA. Equations were employed to calculate the LCA, although ~31% of all studies did not use the LCA model. The appropriateness of a model depends on its price, availability, language, study goals, and user preferences (Yadav and Samadder, 2018). The choice of the LCA modeling tool depends on the research goals, tool acquisition cost, software database usage, and program usability. The LCA model is often used for environmental management systems because it has various benefits besides environmental impact analysis, namely the identification of weak points and improvement opportunities at problematic stages, allows the identification of weak points in the identified waste management system. Therefore LCA can find stages that have poor environmental impact and performance. Furthermore, this model can also be a tool for decision-makers, providing relevant and accountable information for decision-makers. By providing scientific data and analysis on a waste management system's environmental

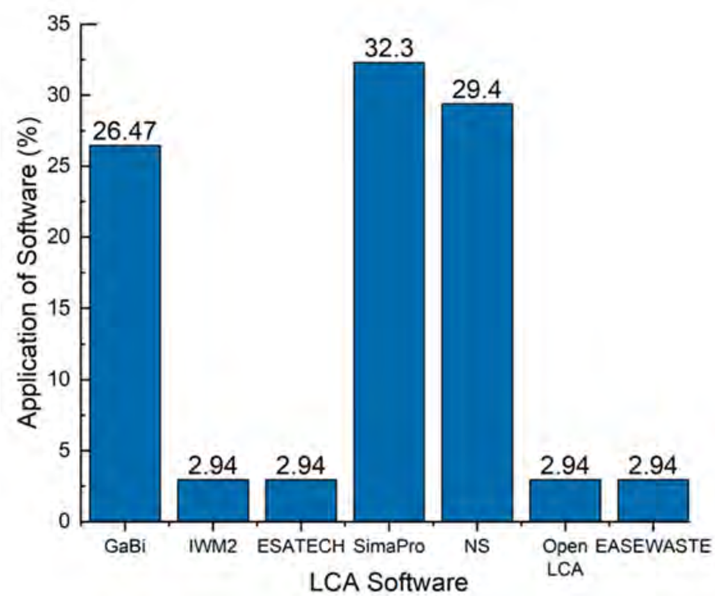

Fig. 6: Life cycle assessment software

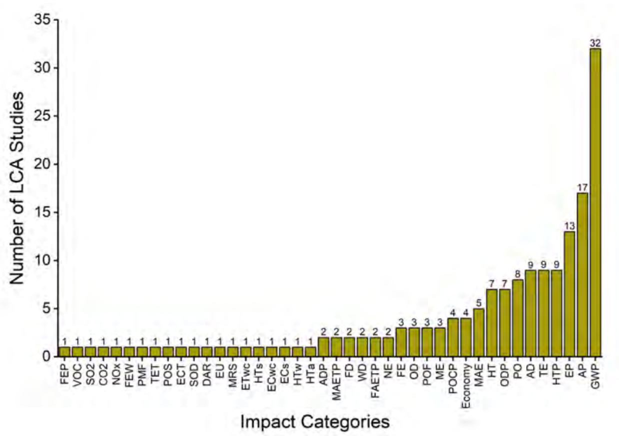

Fig. 7: Impact category

impact, LCA helps inform sustainable and evidence-based decisions. Decision-making based on LCA can consider environmental aspects and contribute to developing a more effective waste management system. Using the LCA model, an environmental management system can be developed and improved by holistically considering environmental aspects.

Impact category selection

The choice of impact categories also falls within the definition of the purpose and scope of the study. However, the broader impact categories make for a more detailed LCA analysis to lead to a sustainable system. Fig. 7 shows how often the impact categories often used in studies for technology analysis are used, with the GWP impact categories being used in impact evaluations related to climate change issues in approximately 96%–98% of the studies reviewed since the GWP is often standardized when considering the potential environmental implications (Yu *et al.,* 2022). More than half of the studies also cover potential human toxicity (HTP) and acidification and eutrophication of water resources, whereas 30% to 35% of studies cover abiotic resource depletion, ozone depletion, and photochemical ozone generation. Approximately 25% of the studies also analyzed other toxicity-related impact categories, such as possible ecotoxicity by water, soil, or water. This rarely used impact category analysis can lead to material substitution and the development of tools in the management of MSW so that it can apply sustainable principles. The study (Pratibha *et al.,* 2019) describes that the main indicators in implementing sustainable and low emissions are greenhouse gas emissions associated with climate change to analyze the impact of technology implementation applied to GWP. Furthermore, energy use to measure the total energy used in each life cycle of the technology used, high energy use can show a significant impact on natural resources and greenhouse gas emissions. The use of natural resources is also an important indicator, which evaluates the use of water, raw materials, and other materials used in implementing technology; excessive use of natural resources can cause a high reduction in crucial natural resources. The formation of waste is also an indicator that is no less important because an increase in the amount of waste produced can indicate problems in process efficiency and efforts to reduce waste, recycle and reuse materials. Air and water emissions are the most frequently used indicators after GWP in accordance with the research results conducted because this indicator includes emissions to air and water produced by the implementation of technology. Examples of emissions produced are in the form of particulates, heavy metals, liquid waste, and various other emissions, which can flow in bodies of water or in the air that is inhaled. From this, indicators of poisoning and health risks are included herein because these indicators can evaluate the potential for poisoning and health risks associated with technology implementation.

Key sensitive parameters

The primary sensitive characteristics are typically based on the current state of the area to be investigated and the availability of technology based on the current state of affairs. However, additional parameters are frequently introduced in the studies under consideration (Elkadeem *et al.,* 2019, Talal *et al.,* 2019). Studies that do sensitivity analysis frequently apply the substitution factor for electrical energy to promote sustainable concepts, as observed in 45%–55% of the papers analyzed. In addition, the composition of MSW, effectiveness of recycling into new products such as compost and animal feed, and energy production/recovery rate from incinerator methods that produce novel resources such as electricity are the most commonly used parameters, with a relatively high level of representation for sensitivity analyses. As shown in Fig. 8, numerous

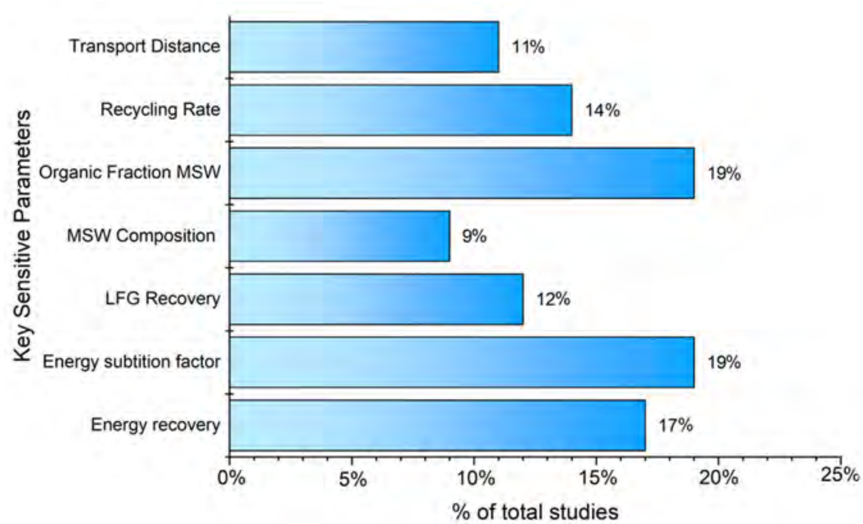

Fig. 8: Key sensitive parameters, the research that has been looked at and used sensitivity analysis has identified and thoroughly detailed key sensitive parameters that significantly affect the final results

other studies also employed the amount of organic waste in MSW, hauling distance, substitutes for recovered materials, and effects of biogenic carbon are examples of emission and sequestration variables. Among other characteristics, the water content in MSW, MSW's calorific value, and anaerobic digestion (AD's) ability to produce biogas are frequently utilized in research to increase the sensitivity of the analysis.

Sensitive criteria importance best fo MSW

Information on the specified subprocesses, the technology used, and the geographic and socioeconomic context are used to determine the effectiveness of MSW management (Iqbal *et al.,* 2020, Rotthong *et al.,* 2022). As explained in the previous section, sensitive parameters are key in the system being analyzed to have a major influence in assessing the potential environmental impact of a technology/policy (Dong *et al.,* 2022, Harun *et al.,* 2021). For example, the composition of MSW varies greatly from country to country and is most important in all aspects due to the existing conditions and habits of the people (Awasthi *et al.,* 2022, Ramos and Rouboa, 2020). This impacts crucial elements that impact on emissions, including heating value, moisture content, the proportion of organic and inorganic debris, etc. (Sgarbossa *et al.,* 2020, Mayer *et al.,* 2020). Regarding the potential for energy and resource recovery as well as environmental emissions, this metric is crucial for all processing processes (Razzaq *et al.,* 2021, Jaunich *et al.,* 2020). The composition of MSW may therefore indicate integrated approaches for separation, recycling, or processing in MSW management (Wang *et al.,* 2022, Paes *et al.,* 2020). For instance, waste with a high organic content can be treated again for new materials and energy recovery (composting, AD, etc.). The content of the MSW can help decide the optimum integration strategy because some products made of metal and plastic can be recycled and utilized as raw materials, such as in the production of concrete. Technology's ability to recover energy and energy replacement variables are crucial, and they may differ between places depending on available technology, environmental factors, fuel blending techniques used in local energy production, and newly discovered energy resources. (Ding *et al.,* 2021, de Sadeleer *et al.,* 2020). Therefore, technologies that are more attractive because of their high energy recovery potential, such as incineration and AD, depend heavily on these factors (Pheakdey *et al.,* 2023). Without energy recovery, this technology is not very attractive and has high side effects such as environmental impact, especially for incineration because of its high cost and emissions (Pheakdey *et al.,* 2023, Hoang *et al.,* 2022); therefore, for the optimum MSW treatment, methods other than incineration will be considered. Like the preceding illustration, energy recovery technology's environmental benefits are lessened if energy is produced using methods based on sources cleaner than fossil fuels, such as hydropower. (Siwal *et al.,* 2021) such as incineration or landfill technologies that produce new energy. The same is true for recycling methods and material substitution factors. Stakeholder policies must consider the supply and demand for recycled materials because the market often uses new materials due to quality problems (Hermansson *et al.,* 2022, Tonini *et al.,* 2022). Countries with high per capita income show competition between recycling and energy recovery methods, to be observed because it has a higher calorific value (Halkos and Petrou, 2016). As a basic example, plastic and cardboard are one of the main raw materials for combustion in energy production by the incineration method. However, if the criteria for being a raw material for incineration are not met, in that case, they can be recycled for use as other raw materials or molded or made into other forms. Energy recycling and recovery techniques for MSW management are an efficient combination and should complement each other based on local demand. Other factors include the transportation distance from the collection point to the management facility, which is also crucial in various regional conditions. Because the new policy may involve other techniques suitable for MSW, increasing the frequency and distance of transport can have direct environmental and socioeconomic impacts that are not foreseen (Omer, 2010). Before choosing the most effective MSW management strategy in these circumstances, LCA experts and policymakers should discuss a thorough assessment of the technical elements and local conditions that influence them. Subjectivity in evaluating environmental protection, cost of capital, and societal acceptance vary between low and high-income countries so that it can generate technological or policy choices that benefit society and the environment.

Guideline for best practices for MSW management

Various variations in technological developments, the geographical characteristics of the country as well as the population's socioeconomic situation, conclude that it is difficult to apply a centralized method or policy in MSW management in various regions (Vance *et al.,* 2022, Baustert *et al.,* 2022). These variations necessitate adjusting the application of the technology required for effective MSW management. Additionally, a nation's weighted preferences in relation to shareholders are used to determine which management technique to implement. For the optimum implementation of MSW management for policymakers, however, critical and valuable implications are required based on the critical analysis of numerous scientific studies from developing to developed Asian nations. Crucial considerations in MSW selection can help address challenges associated with greenhouse gas emissions, resource depletion, and emissions arising from MSW management technologies. Some methods used in overcoming this problem, such as MSW Technology, can involve recycling and energy recovery processes from waste. Recyclable materials such as paper, plastics, metals, and glass can be coated by efficiently separating and treating waste, reducing the demand for new raw materials and the emissions associated with new production. Composting, the application of efficient composting technology in MSW management, allows for the controlled treatment of organic waste and the reduction of methane gas emissions while producing a valuable and sustainable product in the form of compost. Furthermore, approaches such as pyrolysis technology, gasification, or other processing can handle difficult waste that cannot be thermally reproduced. This process can convert waste into alternative fuels, gases, or chemical products that can be used in industry, reducing resource depletion and associated emissions. Implementing a sophisticated monitoring and control system can aid in monitoring and controlling emissions and pollution caused by the management of MSW. Corrective measures can be taken with accurate monitoring to minimize negative environmental impacts.

Reviewed technology

Various existing conditions and new technologies have diverse the technologies used in MSW waste management worldwide. The type of technology and the number applied from the various studies reviewed is shown in Fig. 9. It is evident that technologies have advanced from landfill to more advanced treatment methods like engineered backfill to generate electricity, as well as multiple thermal and biological processes with resource recovery systems, from the source to waste separation, recycling, treatment, and final disposal. Overall, these results cover both centralized methods and scenarios involving MSW management methods analyzed by LCA experts in potential environmental impact assessments.

Best MSW management technologies/facilities

The purpose of selecting all studies from a total of 34 that were analyzed was to identify the best MSW management technology in terms of environmental sustainability for handling MSW. This classification is done to make objective comparisons between various waste management scenarios and get reliable results. The classification of the reviewed research indicates that the optimal scenario for managing MSW in terms of sustainable development is represented by Fig. 10. It can be seen that more than half of the studies analyzing the combination of technologies concluded that an integrated MSW (IMSW), i.e., integrating several technologies to manage MSW, is the best-case scenario in terms of MSW management and an eco-friendly concept (Asefi *et al.,* 2020, Weihs *et al.,* 2022). The summary results obtained from Table 2 and Fig. 9 explain that the use of a single centralized technology in the management of MSW as in traditional practice has relatively low efficiency; technology integration with a combination of several methods is the best approach to develop environmentally friendly principles (Arabi *et al.,* 2021, Colangelo *et al.,* 2021). An integrated approach with several methods helps to achieve efficient and environmentally friendly waste management practices, such as recycling of goods, resource recovery, and reducing the amount of final waste disposed to landfills which can pollute the environment more highly. This principle is in line with research (Saha *et al.,* 2021, Lai *et al.,* 2022) which analyzes the potential environmental impact of several new technological references such as pyrometallurgy, hydrometallurgy, biometallurgy in the management of MSW and combination of old methods such as LF, COMP, MRF and AD to obtain a combination method that has better advantages and higher management efficiency (Lai *et al.,* 2022, Saha *et al.,* 2021, Tabelin *et al.,* 2021).

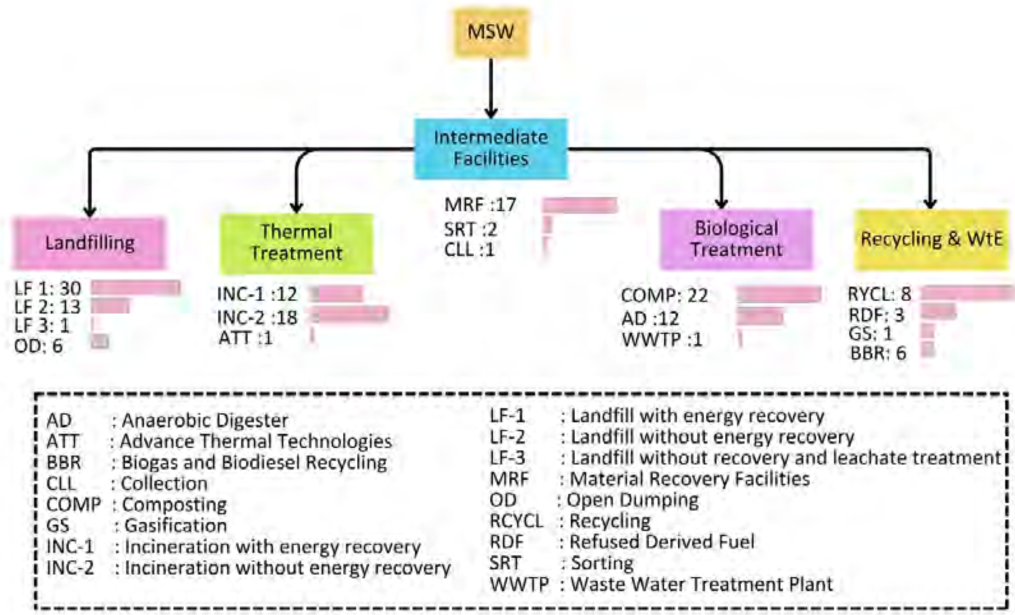

Fig. 9: Types and quantities of MSW treatment technologies under evaluation (Iqbal *et al.,* 2020)

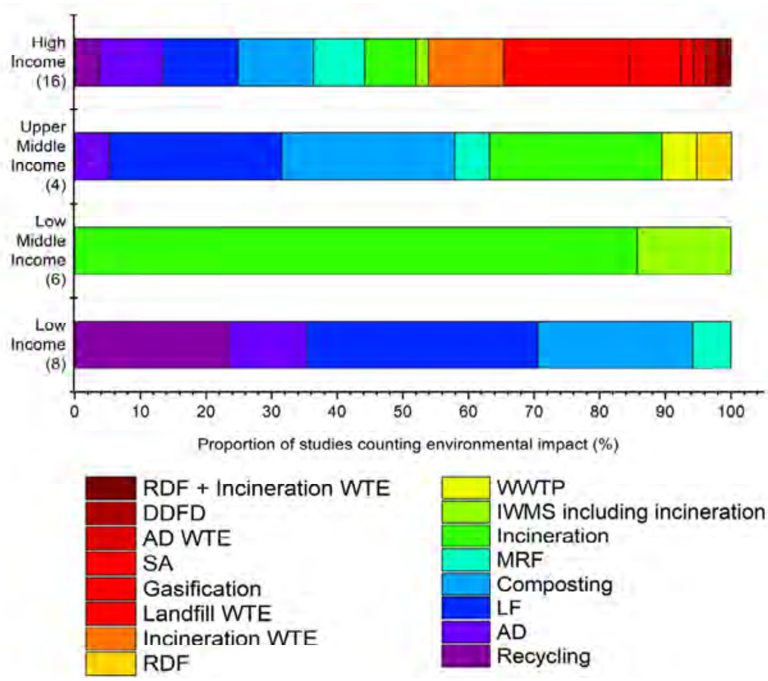

Fig. 10: Proportion studies counting the environmental impact

IMSW technology is used to measure and evaluate the environmental impact associated with the stages of MSW waste management. Examples of how IMSW can be used at each stage are; i) Collection and transportation waste generation measurement technologies and collection route monitoring can be used to estimate the volume and composition of waste collected; ii) Processing and sorting, used to identify the type of waste that goes into processing and segregation, thereby facilitating a more effective sorting process; iii) Recycling and energy recovery involving the use of identification and classification to separate recyclable materials from combined waste to produce compost and electricity; iv) Integrated technology with sensors for remote monitoring of IMSW applied to landfills to detect and reduce methane emissions; v) Utilizing data and analytics, as well as analytics technology to support IMSW, can be used to monitor and evaluate waste management performance, identify potential enhancements, and strengthen decision-making based on evidence. IMSW can provide more precise and comprehensive data regarding the environmental impact of each MSW waste management stage by utilizing sensors, monitoring, data analytics, and simulation software. This allows for wiser decision-making and more effective waste management actions. For example, an ideal MSW management could consist of a combination of methods such as recycling (centralized source or segregation) to separate organic and nonorganic waste, biological treatment (AD, COMP) to process organic waste into new materials or resources, as well as incineration (with energy recovery and concrete), stockpiling (with leachate collection and LFG systems) as the final part of MSW management. Technology such as advanced incineration facilities that generate energy requires large initial capital investment, operating and maintenance costs, and a skilled workforce in implementation, making this method unfeasible for low-income and lower middle–income countries. Conversely, low-income countries may replace MSW management without incineration but should develop schemes that promote the recovery and recycling of MSW's inorganic and organic fractions of MSW. One of the main causes of landfill pollution is the enormous and diverse volume of organic waste that makes up MSW in both industrialized and developing nations. Therefore, recycling organic waste by biological technologies (AD and/or composting) has the benefit of recovering resources (energy/compost), significantly reducing pollution, and reducing the amount of landfill space needed, allowing for effective use of the output generated (Van Fan *et al.,* 2020, O'Connor *et al.,* 2021). Social issues, including political will, job creation, public annoyance (noise, odor, traffic intensity), occupational health, etc., can also affect how local stakeholders, like the government, businesses, and citizens, implement policies. The application of advanced technology/ideal scenario compared to conventional methods was chosen from the various methods analyzed because it has a relatively low environmental impact. Applying the method due to the emission of greenhouse gases can reduce these emissions significantly compared to the traditional method of open burning and stacking in landfilling. Furthermore, reducing emissions into the air and soil, Traditional waste management often involves direct discharge to the environment, which can cause water and soil contamination. In a systematic MSW system, waste is treated more controlled and can reduce the risk of water and soil contamination. Advanced technology can utilize energy and resources. Such advanced waste management technologies can harness the energy contained in waste, such as methane gas produced from anaerobic digestion. This energy can drive turbines or electric generators, reducing dependence on fossil energy sources and associated carbon dioxide (CO_2) emissions. Finally, the absolute advantage is a significant reduction in waste volume without needing large space for stacking. Even though advanced technology has integrated stages, it always produces final waste that needs to be disposed of in a landfill, so it has problems in the form of managing and transporting waste from sources to landfills which causes problems in the form of air pollution from the use of trucks and other vehicles from the fossil fuels used. Ecosystem damage due to inappropriate waste disposal, such as illegal dumping, can disrupt the lives of living things. By implementing the right technology, such as automated sorting systems, industrial composters, or recycling facilities, IMSW technology can help reduce the negative impact of waste transportation and disposal on the environment.

Gaps and the critical findings on the aplication of LCA MSW management *in Asian Countries*

Fig. 10. illustrates the MSW management technique used throughout Asia. Landfilling is a practice that is

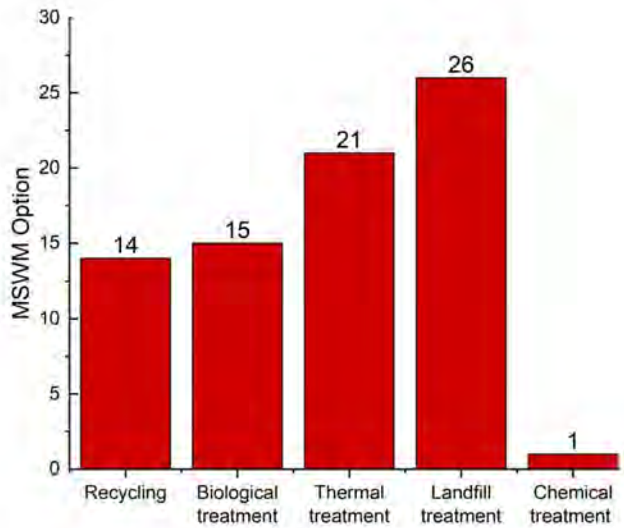

Fig. 11: Suitable MSW management options

widely used and is not environmentally friendly, even though it produces sustainable management. The results of integrated management are very efficient but expensive; hence, hoarding remains the preferred option (Khandelwal *et al.,* 2019). MSW disposal techniques such as landfilling and open burning significantly affect the amount of methane gas produced, significantly affecting human health and environmental sustainability (Premakumara *et al.,* 2018, Cogut, 2016a). One-third apply scenarios using landfilling without further management and open burning for handling MSW, and most are based in LMI countries; this is because integrated management cannot be carried out due to the relatively high cost of producing new resources such as electricity from the incineration method (Menikpura *et al.,* 2013, Ferronato and Torretta, 2019). Fig. 8, as presented in Tables 2 and 3, illustrates the many uses of MSW to make waste into an energy source during the previous decades. To create energy, most of the studies continue to use incineration scenarios with relatively high initial investment. In contrast, only 12 and one study use LFG and gasification scenarios, respectively, due to technological limitations and relatively higher investment in incineration methods due to LFG implementation, which requires various technologies in gas absorption. However, the benefits of this method can be maximized because the gas that arises from the landfill can operate the landfill itself and several surrounding buildings, as was done by (Alzate-Arias *et al.,* 2018, Khandelwal *et al.,* 2019) utilizing LFG to run the landfill and the Federal Bureau of Prisons' Allenwood Correctional Complex. Based on investigations into converting landfill gas into energy, several studies have shown that landfill management can be the optimal solution (Manasaki *et al.,* 2021, Kormi *et al.,* 2017). Furthermore, countries that still use the MSW management technique followed by a combination of recycling and composting or combined and classified as the deepest IMSW get better waste management with minimal or without environmental impact (Safar *et al.,* 2021, Amin *et al.,* 2023). Most studies demonstrated that biological treatments, such as composting and anaerobic digestion, are more beneficial than thermal treatment and landfill. Similarly, most of the 40%–47% of studies analyzed using combined methods fall under IMSW due to the heterogeneous nature of the municipal waste (Njoku *et al.,* 2018, Srivastava and Chakma, 2020). One ideal stage not covered in various cited journals is reducing waste at its source. To handle this, several strategies can be used in the form of reducing packaging practices, avoiding products with excess packaging or using alternatives in the form of recyclable packaging; prioritizing the recycling of materials that can still be used in the form of plastic, metal, and glass; take advantage of available garbage programs even with minimal infrastructure resources; encouraging innovation and environmentally friendly technology.

RECOMMENDATION

As a comprehensive strategy, IMSW incorporates several waste management techniques, such as waste reduction, recycling, composting, and controlled disposal. Composting is the most effective recommendation for treating household and green waste from plants and gardens. It produces organic fertilizer useful for agriculture and horticulture. Thermal processing, such as pyrolysis and gasification, can convert energy into new forms, such as gas, oil, and electricity. Hazardous waste management infrastructure is crucial to prevent hazardous waste from polluting the environment. It includes safe collection and processing facilities for waste in the form of batteries, hazardous chemicals, and electronic waste. The IMSW method shows very efficient results for MSW management, but these results can only be applied to countries with relatively high incomes. The successful implementation of IMSW in high-income countries can be supported by several important factors in the form of adequate policies and regulations; a solid legislative and regulatory framework for MSW waste management comprises mandated recycling, waste reduction, hazardous waste management, and complex structures; includes strict waste management standards, permits, and monitoring. Additionally, a "high-income country" must have adequate infrastructure in MSW waste management, including efficient waste collection, cutting-edge recycling centers, and energy recovery facilities. This method promises to be effective, efficient, and environmentally friendly, with outputs in the form of renewable energy and minimizing negative environmental impacts. The IMSW method can be adapted for low-income countries taking into account the country's specific resources and challenges. Some of the scenarios that are applied to low-income countries and remain effective are in the form of a thorough situational analysis of the country's existing MSW waste management system, which includes existing policies, level of community participation, and waste management. Strategic planning focuses on plans for reduction, recycling, and safe and efficient management. In this case, it requires prioritizing steps with limited resources. Furthermore, a waste sorting and processing system is designed on the available resources. For example, create a simple recycling center to process waste that can be recycled. Even with limited resources, hazardous waste management is crucial to create a safe treatment facility to dispose of and recycle hazardous waste. Form partnerships with the private sector, nongovernmental organizations, and local communities for additional resources and technical support. This collaboration can significantly increase the effectiveness and sustainability of the IMSW system. Next, monitoring and evaluation can be carried out on areas needing improvement and necessary adjustments. Convincing countries to implement the recommended methods for sustainable MSW management does require effective effort and clarification. Education and information play a vital role in this regard. With clear and complete information on the benefits and advantages of the proposed techniques for sustainable MSW management, educate decision-makers and stakeholders about the environmental, economic, and social aspects of executing a sustainability plan. Assist the country/territory in strategic planning, regulatory support, and promotion of sustainable management of MSW. The government helps create supportive policies, proper legislation, and regulations for sustainable MSW management. To help the country adopt the proposed ways, form partnerships with governments, international agencies, NGOs, the commercial sector, and other sustainability-supporting sectors. In its application, an alternative analytical method is needed to assess the life cycle of the waste management system, such as Life Cycle Cost Analysis, which combines economic analysis and LCA to evaluate the costs of various sustainable waste management options. Life cycle energy analysis involves evaluating the energy consumption of the life cycle of a waste management system. *Social life cycle analysis* is an alternative that needs to be considered because this method considers people's welfare, social inequality, employment opportunities, and public participation. IMSW allows for diminished environmental impact, increased resource efficiency, and enhanced waste management sustainability. A comparison of IMSW and a single technology from the citation literature yields very different results. Application of IMSW that is appropriate for each category of MSW waste, such as composting for organic waste, thermal methods for waste that is difficult to process and produces products such as electricity, integrated waste segregation that can still be used, development of landfills to convert into electricity, and collaborations by third parties, governments, and stakeholders are significant steps towards achieving the goal of "sustainable."

CONCLUSION

To provide methodological guidelines for carrying out an extensive LCA on MSW management systems, this review has looked at scholarly literature from all of the Asian nations that are currently available. The most effective approach according to each country's current and economic conditions has been identified using a rationalized technology/strategy ranking based on the evaluation results of many study categories. Based on the factors analyzed, implications and suggestions are given for the most suitable implementation in managing MSW based on the factors analyzed. The corresponding sections provide step-by-step descriptions of the LCA approaches examined in the research as well as comparisons of their differences. Meanwhile, this section briefly discusses several significant issues of establishing best practices for putting LCA for managing MSW into practice. Ensuring precise definitions and analysis goals—subjective and dependent on study goals—is a crucial stage in every LCA study. The study's scope comprises functional units, data selection, impact category selection, etc. Limitation differences are based on particular assumptions related to the goals of the studies. The study's depth is increased by the wider system boundaries and the variety of impact categories, but this also introduces uncertainty into the conclusions. To avoid bias, practitioners must be consistent in their evaluation of the scenarios to be examined. Sensitivity analysis is therefore required to determine the importance of the assumptions made about certain aspects in the study. Choosing one technology over another in the management of MSW is, therefore, something that needs to be studied, especially if this study's goal is to make decisions. Another important factor that needs to be further examined is the evaluation of the economic impact scenario because it affects state income. The analysis's concluding section chooses the optimum approach for managing MSW. The analysis findings revealed that a combination of IMSW management for recycling and resource generation (COMP, INC, AD), Collaboration and Partnership is the thing the author suggests in planning for sustainable MSW. Build partnerships with governments, international agencies, nongovernmental organizations, the private sector, and other sectors that support the concept of sustainability to support the country in implementing the suggested methods. Collaboration can involve exchanging knowledge and experience, technical assistance, training, and access to necessary financial or technological resources, intending to reduce the waste generation in landfills, which is necessary to achieve high environmentally friendly principles. This method is suggested as the most appropriate one to use in Asia. Costly technologies that demand highly qualified workers are only advised for high-income countries. In order to reduce the amount of waste sent to landfills, low-income countries should focus on waste reduction strategies such as recycling, waste banks, and approaches consistent with their current practices. Some of the scenarios that are applied to low-income countries and remain effective are in the form of a thorough situational analysis of the country's existing MSW waste management system, which includes existing policies, level of community participation, and waste management. Landfilling is the final resort for managing MSW, yet it is inescapably a part of the waste management hierarchy and cannot be eliminated from the system since it is the simplest way to manufacture garbage, even though it is not a form of new energy. The application of IMSW is very significant in the environmental impact assessment process of MSW waste management throughout its life cycle. From the various technologies, the scenarios and recommendations reviewed have significant benefits in the form of a more comprehensive identification of environmental impacts. Evidence-based decision-making from information obtained through environmental impact assessments enables more accurate and evidence-based decision-making in developing waste management policies and strategies. Development of sustainable solutions, data, and information obtained through assessments can be used to increase efficiency, minimize pollutant emissions, increase recycling and introduce more environmentally friendly processing technologies. This method's effectiveness is influenced by local, existing variables, a nation's socioeconomic condition, and other considerations. A technology or policy's environmental impact may be influenced by significant factors that are different from the impact criteria. Moreover, the social preferences of stakeholders, including shareholders, the government, and citizens, impact on how policies are implemented. Because of this, making the best option for a nation depends on considering the economic, social, and environmental effects made by decision-makers. The analysis results reveal important factors in selecting the LCA's field of applicability. Insights for creating sustainable MSW management systems are also provided, allowing LCA practitioners and stakeholders to influence public policy in Asia.

AUTHOR CONTRIBUTIONS

M.A. Budihardjo is responsible for making MSW waste management distribution maps in Asia, writing initial drafts, and preliminary research. I.B. Priyambada is responsible for finding out the outline of each manuscript analyzed in managing MSW, determining bibliographical searches, compiling concepts, reviewing all manuscripts. A. Chegenizadeh is responsible for finding out the outline of each manuscript analyzed in managing MSW, determining bibliographical searches, compiling concepts, reviewing all manuscripts. S. Al Qadar reviewed the final report. A.S. Puspita Puspita is responsible for preparing drafts, journal analysis sources and reviewing the entire manuscript.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Per cent
AcRR	All component resources recovery
AD	Anaerobic digestion
ADP	Abiotic depletion potential
AL	Aerobic landfilling
AP	Acidification potential
ATT	Advance thermal treatment
BBR	Biogas and biodiesel recycling
BLF	Bioreactor landfill
CDS	Control disposal site
CLL	Collection
CO_2	Carbon dioxide
COMP	Composting

CROESB	Carbonthermal reduction oxygen enriched side blowing
DAR	Depletion of abiotic resources
DDFD	Directional deploymerization flocculatuon demulsification
DWR	Dry water recycling
Ecs	Ecotoxicity soil
ECT	Eco-toxicity
Ecwc	Ecotoxicity soil
EP	Eutrophication potential
Etwc	Ecotoxicity water chronic
FAETP	Freshwater aquatic ecotoxicity potential
FD	Fossil depletion
FE	Photochemical ozone synthesis
FEW	Freshwater aquatic ecotoxicity potential
FW	Food waste
GDP	Gross domestic product
GS	Gasification
GWP	Global Warming Potential
HIC	Higher income countries
HT	Human toxicity
Hta	Human Toxicity air
HTw	Human toxicity water
IMSW	Integrated solid waste management
INC	Incineration
IWMS	Integrated waste management system
KRS	Kerbside recycling system
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LFG	Landfill with gas
LIC	Low income countries
LMIC	Lower middle income countries
MAE	Marine aquatic ecotoxicity potential
MBCS	Material bank collection recycling system
MRF	Material recovery facility
MRS	Mineral resources scarcity
MSW	Municipal solid waste
Mt	Million ton
NE	Nutrient encrichment
NO_x	Nitrogen oxides
OF	Organic Fertilizer
OB	Open Burning
ODL	Open dumping landfill
ODP	Ozone depletion potential
OWM	Organic waste management
PC	Pre-composting
PMF	Particulate matter formation
POCP	Photochemical ozone creation potential
POF	Photochemical ozone formation
POS	Photochemical ozone synthesis
RCYCL	Recycle
RDF	Refused derived fuel
RWM	Residual waste management
SAL	Semi aerobic landfilling
SD	Scatted dumping
SF	Sintetic fertiliezer
SLF	Sanitary landfill
SO_2	Sulfure dioxide
SRT	Sorting
TET	Terrestrial eco-toxicity
t/y	Ton per year
UMIC	Upper middle income country
USD	United States dollars
VOC	Volatile organic compound
WD	Water depletion
WWTP	Waste water treatment plant

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SPECIAL ISSUE: Eco-friendly sustainable management
ORIGINAL RESEARCH PAPER

Management strategies for the efficient energy production of brackish water desalination to ensure reliability, cost reduction, and sustainability

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ABSTRACT

BACKGROUND AND OBJECTIVES: Energy efficiency plays a crucial role in the success and sustainability of desalination technologies. Energy considerations are intricately linked with every aspect of planning, management, and operation in water desalination. This study aims to evaluate and enhance energy requirements, energy efficiency, and the economic feasibility of the Hashemite University photovoltaic brackish water reverse osmosis desalination plant at Hashemite University.
METHODS: This study's aims were achieved by conducting an energy audit and detailed assessment to identify the energy efficiency considerations that should be integrated into the facility's planning, management, and operation strategies. To ensure accurate and reliable data collection and enable a comprehensive analysis of the plant's energy performance, portable energy analyzers and loggers were employed to measure energy consumption, and measurements and verification techniques were recommended and implemented to establish the required baseline. A regression model was utilized to determine the potential energy savings resulting from energy conservation measures. This involved determining the expected savings by calculating the area between two curves: the new actual consumption of the brackish water reverse osmosis plant after implementing energy conservation measures and the curve generated by the model representing the usual consumption in the absence of energy conservation measures.
FINDINGS: This study underscores the challenges faced by desalination, particularly regarding intensive energy consumption. It also presents innovative ways to achieve sustainability by emphasizing energy efficiency, integrating renewable energy, and advocating for a holistic water management approach. It was determined that the maximum specific energy consumption of the Hashemite University photovoltaic brackish water reverse osmosis plant was 0.625 kilowatts per cubic meter. This reflects the actual consumption and energy performance of the plant, which was found to be 192 percent more efficient than the estimated specific energy and 144 percent more efficient than the calculated specific energy. No energy conservation measures were implemented at this stage, as the plant was already operating efficiently. The measured data shall be considered as a baseline for future investigations and monitoring and evaluation of the plant. Many challenges were identified during the current work, including the low quality of raw water and minimal demand for freshwater, which resulted in lower operation hours outside of sun peak hours, while the direct utilization of photovoltaic energy is recommended.
CONCLUSION: Renewable energy and energy recovery were recognized as potential sources for energy savings to achieve sustainable and long-term feasible operation and cost recovery at the Hashemite University photovoltaic brackish water reverse osmosis plant. The feasibility of the plant showed a fast payback period of up to 1.1 years. Utilizing clean solar photovoltaic energy to power the brackish water reverse osmosis plant led to a considerable reduction of greenhouse gases (mainly carbon dioxide). The estimated amount of carbon dioxide reduction during the project's lifetime was 1,289,600 kilograms. The integration of solar energy showed promise for further enhancing energy efficiency and sustainability. This study contributes to making the desalination sector more environmentally friendly and economically viable, which is of paramount importance in addressing global water scarcity concerns.

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54	8	8

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INTRODUCTION

Jordan's government is attempting to meet the future demand for energy through several actions: increased dependence on renewable energy, energy management, use efficiency, finding new energy supplies, financial incentives, and tax exemption to attract investors. Still, some challenges should be taken into account to sustain development, such as the incapability of the current grid to handle the power expansion required by the proposed projects in the near future (Abu-Rumman *et al.,* 2020). According to a Bloomberg report, Jordan has the potential for solar and wind energy use and is one of the leading countries in the adoption of clean energy. So far, the implementation of renewable energy has been successful due to financial incentives, tax and customs exemptions, technical and financial assistance from foreign aid and international agencies, and political and economic stability (Sandri *et al.,* 2020; Drobyazko *et al.,* 2021; Ramli *et al.,* 2022). In 2015, 20 percent (%) of the national budget was consumed by the energy sector, but it was reduced to 10% in 2018 due to the adoption of energy efficiency measures and the increased contribution of renewable energy to the national power mix (Abu-Rumman *et al*., 2020). Fig. 1 shows that in 2020, 21% (about 2,400 megawatts, MW) of electricity was generated from renewable energy resources. To encourage households' installation of renewable energy systems, the Ministry of Energy and Mineral Resources (MEMR) subsidized installation costs by 30%. As a result, 500 thermal solar systems and 1,888 photovoltaic (PV) systems were installed. Moreover, 200 solar systems were installed in rural areas for free, and the cost was equally covered by the MEMR and the International Union for Conservation of Nature (MEMR, 2021). The growing adoption of renewable energy reflects a positive trend toward sustainability and reduced reliance on fossil fuels for power generation (Elsaid *et al.,* 2020; Bogachov *et al.,* 2022; Sivakumar *et al.,* 2022). It also highlights the progress made in transitioning toward a cleaner and more environmentally friendly energy sector.

Solar radiation is widely utilized for water heating purposes and PV electricity generation systems (Ahmad and Schmid, 2002). PV systems have some advantages that make them preferable, such as an absence of moving parts, ease of installation and operation, low maintenance costs, pollution-free operation, and long operation life (Qiblawey *et al*., 2011). The amount of power produced by PV systems depends on the panels' performance and the availability of solar radiation (Alrwashdeh, 2018). In Jordan, direct solar radiation intensity ranges from 5 to 7 kilowatt-hours per square meter (kWh/m²), with an average of 310 sunny days (Abu-Rumman *et al*., 2020). Jones *et al.* (2016) conducted a simulation model of a PV system in a water pumping and desalination plant for agriculture purposes in selected areas in Jordan Valley and then compared this system with diesel-powered and grid-powered systems. The result was that PV-powered systems were more economical than diesel-powered systems but less economical than off-grid-powered systems based on assumed electricity costs. It was found that PV-powered pumping and desalination plants become profitable with high-return crops when pumping from a shallow well with low water salinity and a low water requirement in areas where solar insolation is high. According to a study by Alrwashdeh (2018), in which solar energy generation was evaluated in different major Jordan governorates (Irbid in the north, Amman in the center, and Aqaba in the south), the annual solar radiation was 1,876 kWh/m² in Irbid, 1,967 kWh/m² in Amman, and 2,151 kWh/m² in Aqaba, and the generated electricity for a fixed configuration per a certain single PV module during the year in Irbid, Amman, and Aqaba is 359.3, 443.1, and 502.0 kWh. Another use for solar radiation is solar ponds, per the study by Saleh *et al.* (2011). The study investigated the performance of a salt ingredient solar pond coupled with desalination plants near the Dead Sea. It was found that the plant could produce 4.3 L/min on average. In conclusion, this type of thermal desalination seems feasible and appropriate under Dead Sea conditions. There is no doubt that Jordan urgently needs desalination to meet the growing demand, and Jordan can utilize renewable energy resources, especially solar and wind energy (MoEnv, 2020a; MoEnv, 2020b). As a water- and energy-scarce country, Jordan must work on brackish and seawater desalination in conjunction with renewable energy resources to supply such technology with the power needed (MWI, 2021; Al-Kharabsheh, 2020). A comprehensive database is needed to be able to utilize them properly. Such energy sources could supply Jordan with its daily electricity requirements and reduce GHG emissions (Baniyounes, 2017). Jaber

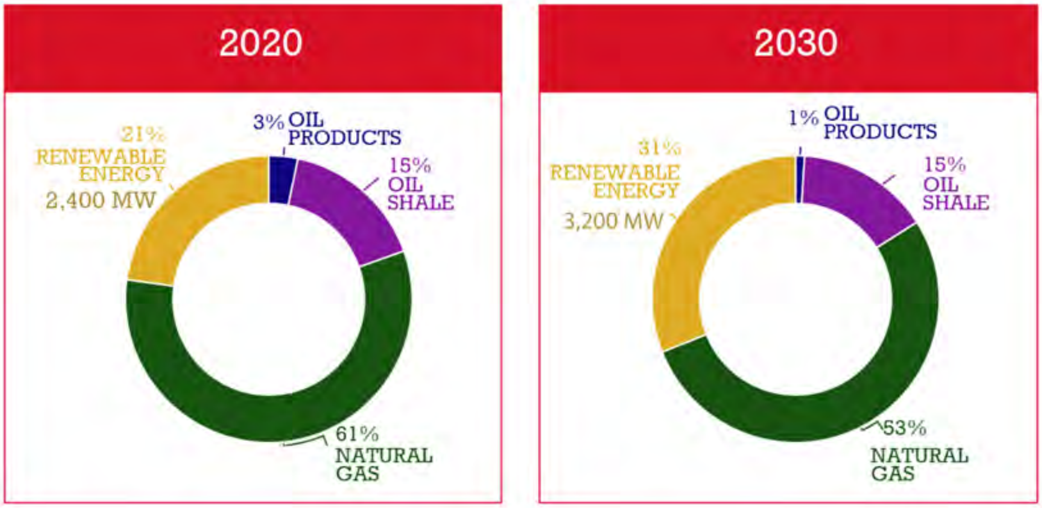

Fig. 1: Renewable energy contribution ratio to electricity generation (2020–2030) (MEMR, 2021)

et al. (2015) conducted a SWOT analysis showing the strengths and weaknesses of Jordan's renewable energy market and illustrated the opportunities and threats. Compain (2012) presented different solutions to the most used desalination processes—reverse osmosis (RO), multi-stage flash distillation (MSF), and multi-effect distillation (MED)—coupled with solar energy production technology compatible with desalination. The goal is to assess the feasibility and profitability of the substitution of fuel energy used for desalination plants with renewable energy. A review of various technologies broadly defined features associated with each technology and the range of cost that is expected and included a review of various projects detailed the practical aspects of floor space and the actual production costs of fresh water. Luo *et al.* (2021) presented solar-thermal evaporation as a traditional steam generation method for solar desalination, which has received much attention in recent years due to the significant increase in efficiency achieved by adopting interfacial evaporation. While most previous studies have focused on improving evaporation efficiency through material innovation and system design, the underlying mechanisms of energy efficiency are underexplored, leading to much confusion and many misunderstandings. It was found that, overall, the solar desalination efficiency of interfacial evaporation in a solar system is still not as high as expected; further improvement is possible from the system design perspective. The analysis provides insights into the thermal processes involved in interfacial solar evaporation and offers perspectives on the further development of interfacial solar desalination technology. Naderipour *et al.* (2021) introduced a framework for designing a photovoltaic-based water pumping system to supply customers in remote areas with drinking water. Their approach minimizes net present cost (NPC) and ensures reliability while using an intelligent water drops algorithm to optimize the system. Simulation results demonstrated the effective sizing of components and storage, achieving optimal reliability and minimal NPC of 3.17%. Goosen *et al.* (2023) provided a review of recent developments in solar desalination from the viewpoint of environmental, regulatory, and economic aspects. Their analysis attempted to give better insight into the larger question of why more solar desalination plants are not being established by reviewing different technologies, drivers, barriers, and markets. Critical barriers that are dependent on the level of regional development were found to be an uncertainty of government subsidies and a lack of regulatory policies. The overall trend was a shift toward the integration of renewable energy with conventional sources and energy storage systems. The primary objective of this study is to optimize energy consumption and enhance the energy efficiency of a hybrid BWRO plant through the integration of energy efficiency considerations into the planning, management, and operation strategies of the facility. Also, this study will investigate the techno-economic feasibility and financial analysis of the plant. Ultimately, this will reduce operational costs and improve the overall sustainability of the plant. Also, it will improve reliability, sustainability, and environmental performance through the more efficient utilization of resources for meeting water demands. This study was carried out at the Hashemite University (HU) desalination plant, Jordan, from 2021–2022. Also, it demonstrates the linkages of water availability and energy supply with production, which are vital needs to ensure a healthy life for communities' livelihoods and represent the basis of the country's socioeconomic and ecological resilience.

Optimizing energy efficiency and sustainability in hybrid BWRO desalination plants

Brackish water desalination has become a crucial necessity, but its success hinges on meticulous planning and effective management to avoid systemic deficiencies that undermine performance, increase costs, and cause unexpected downtime (Usman *et al.,* 2021). Failure to address these deficiencies can lead to critical shortcomings in the realization and operation of desalination facilities, compromising their ability to meet local and regional water demand requirements (Okampo and Nwulu, 2021). During operation, the abstraction scheme may prove incapable of delivering the intended quality and quantity of raw water (Wang *et al.*, 2019). Comprehensive planning must encompass various key elements (Fig. 2) to mitigate these challenges.

By emphasizing adequate planning and operation, costs can be reduced, as planning expenses constitute only a fraction of the total investment in desalination facilities (Al-Karaghouli and Kazmerski, 2013). Optimized tendering documents, aligned with market conditions, can yield significant savings if all necessary planning steps are executed properly. System failures and the limited availability of source water disrupt water supply stability and inflate costs, necessitating sustainable and stable operations (Pugsley *et al.*, 2016; Moghadam and Samimi, 2022). High plant reliability requires substantial investments to be made in process equipment, automation, and control systems, minimizing power outages, unsafe operations, and equipment damage (Tao *et al.*, 2018). Regardless of the desalination technology employed, whether thermal or membrane-based, desalination remains an energy-intensive process, as it impacts the overall cost, reliability, sustainability,

Fig. 2: Key elements in planning and management for efficient and reliable brackish water desalination

and environmental footprint of the desalination technology (Mahmoudi *et al.,* 2009). Fig. 3 illustrates the linkage between energy efficiency and various aspects of planning, management, and operation strategies in water desalination. Obviously, energy is critical and connected with all six strategic planning and management phases (Mohammad *et al.,* 2021). For example, comprehensive planning involves the selection of desalination technologies that prioritize energy efficiency. Engineers can optimize the plant's energy efficiency for the initial stages by assessing design considerations that are relevant to energy consumption (Manju and Sagar, 2017; Amani *et al.,* 2021). Meanwhile, optimal system design includes the layout and configuration of the plant to minimize losses and improve the plant's performance. Advanced process control continuously monitors and optimizes plant operations by modifying key parameters while maintaining produced water quality according to standards (Bdour *et al.,* 2022). Maintenance and optimization address issues of proactive maintenance practices, implementing energy audits to identify energy drops to ensure operation at optimum efficiency levels. Lastly, the training and knowledge transfer phase is related to providing adequate training and knowledge for operators to ensure optimum operation, identify energy-saving opportunities, and employ energy-efficient measures properly (Edris *et al*., 2022).

Most existing active desalination plants in Jordan are reverse osmosis systems with advanced membranes and energy recovery devices (Al-Obaidi *et al.,* 2023). These technologies are energy-efficient, resulting in reduced energy consumption during the desalination process (Saeed *et al.,* 2023). Recent advancements in desalination strive to enhance energy efficiency by reducing the energy consumption per unit of freshwater produced (Bundschuh *et al.,* 2021). One of these attempts includes the coupling of renewable energy sources to drive desalination plants. There is a need to enhance the technical and thermal performance of these technologies through comprehensive analysis and industrialization. The integration of renewable energy sources with a traditional desalination system requires continuous research and development to improve their market penetration and cost-effectiveness (Shokri and Fard, 2022).

Fig. 3: Illustration of the linkages between energy efficiency and various aspects of planning, management, and operation strategies in water desalination

Description and pre-assessment of the HU PV-BWRO plant

Plant design and general layout

The Hashemite University photovoltaic brackish water reverse osmosis (HU PV-BWRO) desalination plant has been designed to have a total capacity of 1,992 cubic meters (m^3) based on full operational hours. It has been assessed that the domestic water consumption of the HU campus, determined during the summer season, is approximately 270–300 cube meter per day (m^3/d), representing the total daily water demand for various domestic on-campus purposes. Also, there has been a shortage of underground water in the HU campus to cover domestic and agricultural water demands. The prolonged deterioration of the Amman-Zarqa basin has affected the water quality of its associated aquifers. In the HU campus, the two main groundwater wells had total dissolved solids (TDS) levels in the range of 1,200–3,500 milligrams per liter (mg/L), which does not comply with Jordan's drinking water standards. An on-grid 53-kilowatt PV solar system has been placed on the rooftop and car park of the desalination building to supply the HU PV-BWRO desalination plant with the required electrical energy. The main BWRO desalination compartments include a raw water tank (100 m^3), a feed pump, five- and 25-micron bag filters (series filtration), an antiscalant tank, a hydrochloric acid (HCL) tank, a high-pressure pump (HPP), a three-stage reverse osmosis (RO) system, an inter-stage high-pressure pump allocated between stage 2 and stage 3 of the RO system, a mixing pump, an aeration tower, a 50-m^3 equalizer tank (treated water tank), a treated water pump, and a caustic soda tank. The system has a three-stage RO configuration, which is designed to have a high recovery of approximately 88% by attaining a permeate flow of about 59 m^3/h, and the reject water is about 8 m^3/h. Permeate is mixed with raw water to obtain a final product of 83 m^3/h with an applicable TDS for domestic use. Flow rate, pressure, potential of hydrogen (pH), electrical conductivity (EC), and TDS sensors are used to measure and monitor feed, permeate, final product, and even the brine reject water before being disposed of in the associated evaporation ponds. The evaporation ponds were estimated to have a surface area of over 5,000 m^2 and a depth of 1.5 m. Table 1 shows the performance parameters assumed by HU BWRO at the total design capacity of the plant.

The quality and quantity of product water and the plant recovery ratio are crucial performance indicators for the desalination plant. However, they are not the sole factors that determine the plant's overall performance and sustainability. Another critical indicator to consider is electrical consumption, as energy usage (electricity) constitutes a significant portion of the operational cost of any desalination plant. Ensuring efficient electricity consumption is of utmost importance to maintain control over the actual specific water production cost of the plant. This guarantee of power consumption is often expressed as a "specific energy consumption," measured in kWh/m^3, which includes all power consumed from the raw water pumps through the final storage tank. The electrical consumption should be carefully evaluated across various components, including the pre-treatment system, desalination system, post-treatment system, and associated infrastructure. Since electrical energy is a significant part of the operational cost of a BWRO plant, it is crucial to optimize the energy consumption of each plant component. Achieving this requires the identification and definition of the various energy consumers within the plant, considering the operating hours of each individual component. By understanding the energy requirements and usage patterns of these components, it becomes possible to implement measures that enhance energy efficiency and reduce operational costs in the BWRO plant. The estimated specific energy consumption (kWh/m^3) for the BWRO station at the HU, as indicated in Table 1, is found to be relatively high. Therefore, it is necessary to propose measures aimed at improving energy efficiency in the BWRO plant and reducing the specific energy consumption (kWh/m^3). It is essential to clearly define the scope and boundaries of the study to achieve

Table 1: HU BWRO performance parameters

Feed (m^3/h)	Permeate (m^3/h)	Final product (m^3/h)	Reject brine (m^3/h)	Plant recovery ratio (%)	Plant Capacity (m^3/d)	Estimated energy consumption (kWh/m^3)
67	59	83	8	88%	1,992	1.2

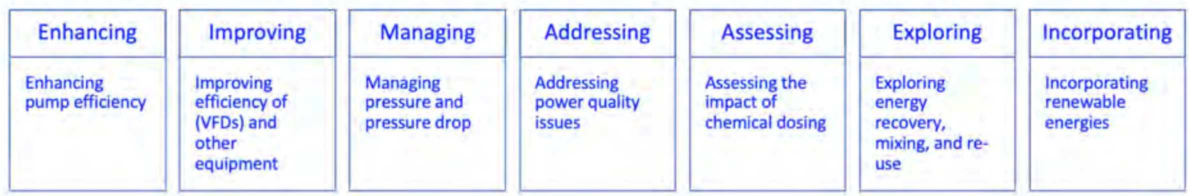

Fig. 4: Opportunities for energy savings in the context of the BWRO plant

these outcomes. This investigation will help identify areas that require improvements and allow for a targeted approach to optimizing energy consumption in the BWRO plant. This study was carried out at the Hashemite University (HU) desalination plant, Jordan, from 2021–2022.

HU-PV BWRO pre-assessment evaluation

After conducting the pre-assessment at the HU-PV BWRO plant, several opportunities for energy savings were identified, as illustrated in Fig. 4. These opportunities include the following areas within the plant.

1. Enhancing pump efficiency: This can be achieved through the utilization of more efficient pumps or by replacing existing pumps with more efficient models. Also, the re-selection of pump sizes based on factors such as power and the best efficiency point can contribute to energy savings (Mohammadi *et al.,* 2021). In some cases, modifications to existing pumps, such as removing stages from multi-stage pumps or using/activating variable frequency drives (VFDs), can also improve efficiency (Razi and Dincer, 2022).

2. Improving the efficiency of variable frequency drives (VFDs) and other equipment: Optimizing the performance of VFDs and other auxiliary equipment can lead to energy savings.

3. Managing pressure and pressure drops: Addressing energy losses caused by friction, mechanical losses, hydraulic energy losses, and water leaks can significantly reduce energy consumption (Gude and Fthenakis, 2020).

4. Addressing power quality issues: Energy losses resulting from power quality issues are to be identified and mitigated to minimize their impact on overall energy efficiency (Goh *et al.,* 2017). Also, measures to reduce heat dissipation, such as improving insulation and optimizing HVAC, lighting, and electrical cable systems, can help conserve energy (Dashtpour and Al-Zubaidy, 2012).

5. Assessing the impact of chemical dosing: Evaluating the influence of chemical dosing in the pre-treatment stage on scaling and fouling of membranes can help optimize the dosing process and reduce energy requirements (Patel *et al.,* 2020).

6. Exploring energy recovery, mixing, and re-use: Implementing strategies for energy recovery, efficient mixing processes, and the re-use of treated water can contribute to energy savings (Alawad *et al.,* 2023).

7. Incorporating renewable energies: Increasing the use of renewable energy sources, such as solar or wind power, can supplement the energy requirements of the BWRO plant and improve overall energy performance (Ghaffour *et al.*, 2014). Also, optimizing operating times and considering energy storage solutions can enhance the efficiency of renewable energy integration (Ahmadi *et al.,* 2020).

By considering these energy-saving opportunities, the BWRO plant can achieve improved energy efficiency and reduce its specific energy consumption (Tayyeban *et al.*, 2022). The SEC of the BWRO unit per hour, indicated in Table 2, was calculated based on the summation of the nominal powers of the pumps within the unit. In practical water applications, pump-motor sets are typically partially loaded, resulting in lower discharge pressures for the same water quantities, as indicated in Table 2. Measurements are necessary to determine the actual specific energy consumption. The BWRO unit is not always operational due to quality issues with the raw groundwater. Also, it is recommended to sustain the operation of the BWRO station at full capacity, especially during peak sun hours, to optimize and balance energy requirements from renewable sources, such as solar energy. Energy meters with energy loggers should be installed for the BWRO unit and the PV system. Displaying energy data on the monitoring system is advised.

Table 2: Monthly energy and water data for the year 2021

2021 month	Treated water (m^3)	Operating hours (h)	PV-produced energy [kWh]	Calculated energy consumption (kWh)	Calculated energy cost (kWh/m^3)	Total power (kW)
JAN	5,072	100	4,250	6,900	1.36	69
FEB	4,482	89	4,982	6,107	1.36	69
MAR	5,443	116	7,142	8,004	1.47	69
APR	6,001	108	8,025	7,452	1.24	69
MAY	5,566	92	9,417	6,362	1.14	69
JUN	4,728	78	9,950	5,351	1.13	69
JUL	5,477	90	9,909	6,213	1.13	69
AUG	4,175	70	9,134	4,820	1.15	69
SEP	5,391	87	7,095	5,986	1.11	69
OCT	5,664	90	6,191	6,189	1.09	69
NOV	4,864	81	4,791	5,568	1.14	69
DEC	5,657	91	3,841	6,262	1.11	69
SUM/AVG	62,520	1,090	84,727	75,213	1.2	69

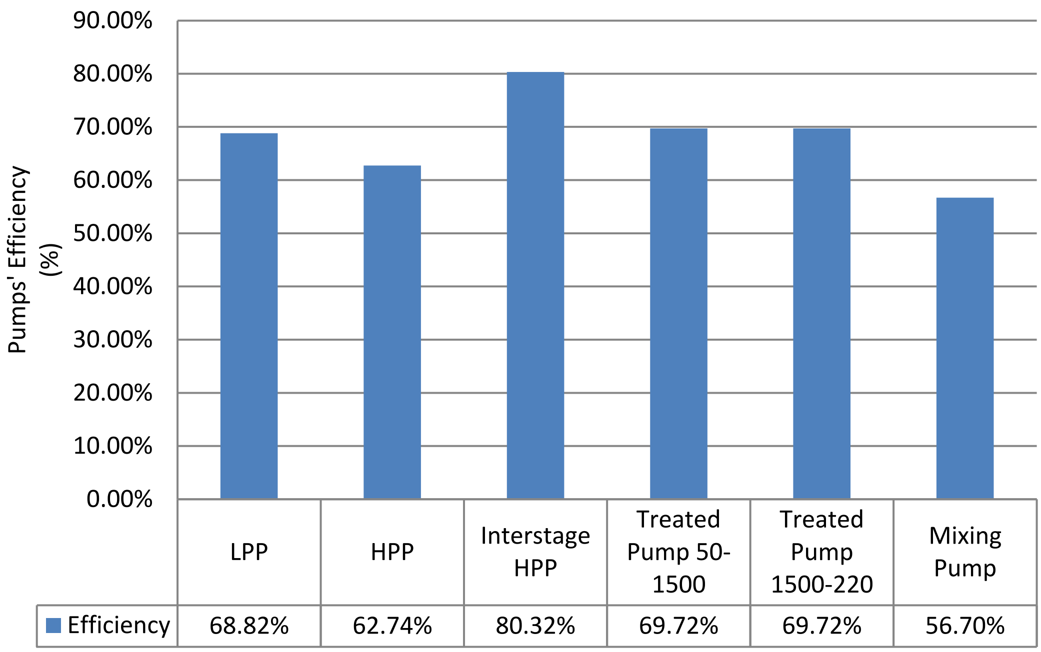

Fig. 5: Pumps' efficiencies at the HU-BWRO desalination plant.

The use of variable speed drives (VSDs) is recommended as an energy-saving measure instead of wasting energy through throttling. The energy consumption of each pump should be measured and monitored to verify the potential for energy saving. Initially, it was observed that the efficiency varies among pumping units. Further investigation is needed to assess the efficiency of each unit individually. Fig. 5 shows the efficiency of the BWRO pumps. It was found that the inter-stage high-pressure pump is the most efficient pump and has 80.32% efficiency, while the mixing pump has the lowest efficiency of the pumps in the BWRO plant (56.7%), assuming that both the inter-stage high-pressure pump and the mixing pump have the same power (4 kW). It is possible to eliminate certain pumps, such as the mixing pump, which would result in power savings. The power of other pumps could be reduced compared to their

Table 3: Calculations of the specific energy consumption for different assumed scenarios in 2021

Pumps	Duty point			Operational		
	Power (kW)	Q (m^3/h)	H (m)	Q (m^3/h)	H (m)	Power (kW)
LPP	9.2	67	30	67	25	7.67
High-pressure pump	37	67	110	67	90	30.27
Inter-stage HPP	4	17	60	17	50	3.33
Treated pump 50–1,500	15	83	40	81	20	7.32
Treated Pump 1,500–220	15	83	40	83	40	15
Mixing Pump	4	24	30	22	25	3.06
Total loads (assumed scenarios):	Total nominal power (kW)	SEC (kWh/m^3)	TW* (m^3)	OH** (h)	Total operational power (kW)	SEC (kWh/m^3)
Loads + Pump 1,500–220	84.2	1.45			66.65	1.16
RO Loads (Pumps) only	69.2	1.21	62,520	1,090	51.65	0.90
Loads – Mixing Pump	65.2	1.14			48.59	0.85

*TW: Treated water for the year 2021

**OH: Operating hours for the year 2021

nominal values.

The current membranes used in the BWRO system are low-energy membranes with negligible energy-saving potential. Energy recovery from the brine can be achieved under specific parameters: namely, a flow rate of 8 m^3/h and a pressure of 11.5 Bar. More data and on-site investigations are required to evaluate the feasibility of implementing such a system. Contrarily, optimizing the use of renewable energy can be achieved through the addition of PV panels and increasing the direct current to alternating current (DC/AC) ratio to enhance energy production. Also, changing the operation time of the BWRO unit to align with sun peak hours and ensuring the regular and efficient cleaning of the PV modules can contribute to improved energy efficiency (Naderipour *et al.*, 2021). Due to the absence of power and energy meters in the plant, the data presented in Table 2 were derived using the nominal power of the pumping units in the BWRO plant, resulting in a specific energy consumption of 1.2 kWh/m^3. An alternative approach was followed to calculate the specific energy using operational data provided by the plant operator, as shown in Table 3. According to this method, the specific energy consumption was found to be 0.9 kWh/m^3. It was discovered that there are other loads associated with the pumping units, with the sum of the nominal powers of the pumps amounting to 69.2 kW, excluding the second treated water pump from the 1,500-m^3 reservoir to the 220-m^3 reservoir. Taking this pump into account, the total power of all pumps in the BWRO plant is 84.2 kW. It is important to consider the scope and boundaries of the study when analyzing the data, which may involve deciding whether to include or exclude the groundwater submersible pump and the treated water pump from the 1,500-m^3 tank to the 220-m^3 tank based on the objectives and focus of the research.

The study methodology

Detailed assessment and energy auditing (EA) require examining the overall efficiency of the plant before implementing any measures toward an energy-efficient RO plant. In the case of HU-BWRO, the energy input can be directly measured from the electrical component, while measuring the energy output requires a specific setup. One method to measure the output energy of the motors, which represents the mechanical energy, is to install two measurement devices at the shaft coupling the motor and the pumps. These devices are capable of measuring and recording the rotational speed and torque to calculate the mechanical energy. The output power equals the torque multiplied by the angular speed. These measurements are helpful when assessing a motor's efficiency. Power measurements can be conducted without following this procedure by measuring the hydraulic data, such as water flows and water pressures, especially when the couplers are not easily accessible. The overall efficiency could be calculated based on the input electrical power and the output hydraulic power. In this study, an energy analyzer was used to measure and analyze power and energy consumption. The initial setup of the

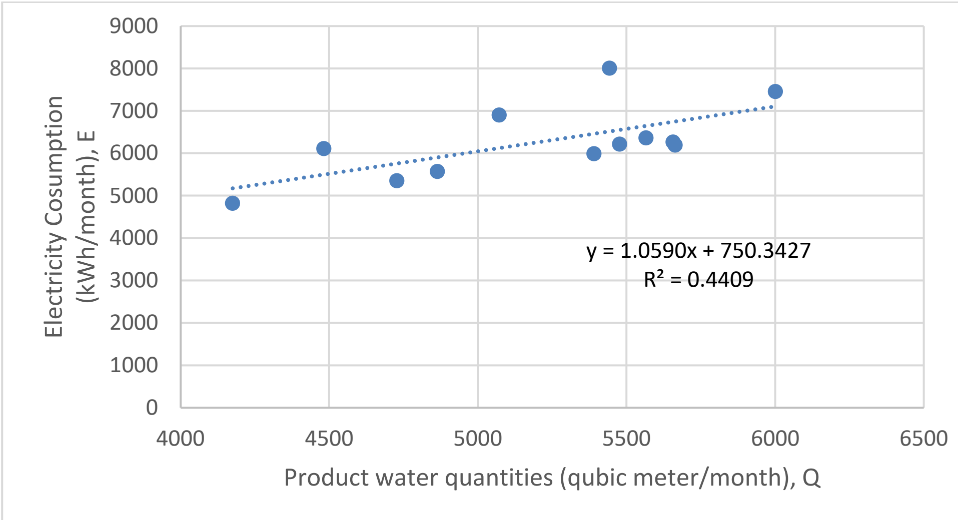

Fig. 6: Baseline model for monthly energy and water data for the year 2021

power and energy analyzer device was conducted to identify various parameters, including details of the electrical system and other measurement and Logger specifications and parameters. Power and energy were measured using a Fluke 438-ii power quality and energy analyzer. Since direct access to the electrical terminals of each pumping unit was not feasible, power and energy measurements were performed on the main power circuit breaker of the BWRO station instead of each pumping unit. The power measurements included were the energy loss calculator, the scope, and the logger. The energy loss calculator provided a summary of losses caused by power quality issues, which were found to be minor in terms of power losses (< 1 kW), with no major poor power quality issues. The scope functioned as an oscilloscope, while the logger was used to record predetermined parameters. This study primarily focuses on measuring the energy and active power consumption of the BWRO to investigate the specific energy consumption at the HU station. The logger, scope, and other collected data are available for further elaboration on specific measurement details and the overall situation. A baseline was established using a regression model implemented in an Excel sheet. Monthly data on energy consumption and treated water quantities from Table 2 were utilized, yielding the results illustrated in Fig. 6.

As shown in Fig. 6, there are different operation characteristics for the months of January to April, which were not correlated or consistent with the data of the remaining months of the year 2021, as R^2 equals 0.4409. Fig. 7 illustrates this gap clearly. Knowing that the BWRO was operated starting from January, it is expected that in the first four months that the plant was operated, the efficiency was improved, and the data became steady.

By excluding the data from the first four months and considering the data from May to December of the year 2021, the data become more correlated, and R^2 equals 0.9747. Fig. 8 illustrates the baseline model for the BWRO plant.

This study focuses on investigating the techno-economic feasibility and financial analysis of the HU BWRO plant, considering self-financing and operation and maintenance (O&M) deduction. The cost savings resulting from this project can be categorized into two parts. The first is savings in water demand costs for the water supplied by the water services company to the HU, amounting to 1.76 USD/m^3 (sewer services provided by the water services company to the HU still incur a cost of 1.2 USD/m^3). The second is the additional savings generated through the electricity produced by the 52.8-kWp on-grid PV system. This study evaluates the total savings attained from PV energy generation and reduced water costs.

Specific energy consumption results

Tables 4 and 5 show a summary of the field

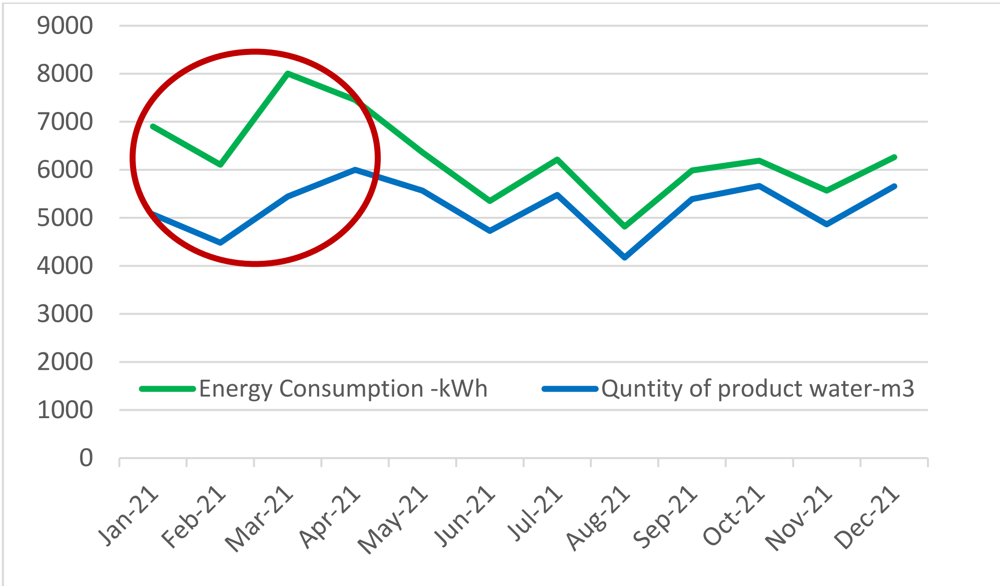

Fig. 7: Baseline model for the monthly energy and water data for the year 2021

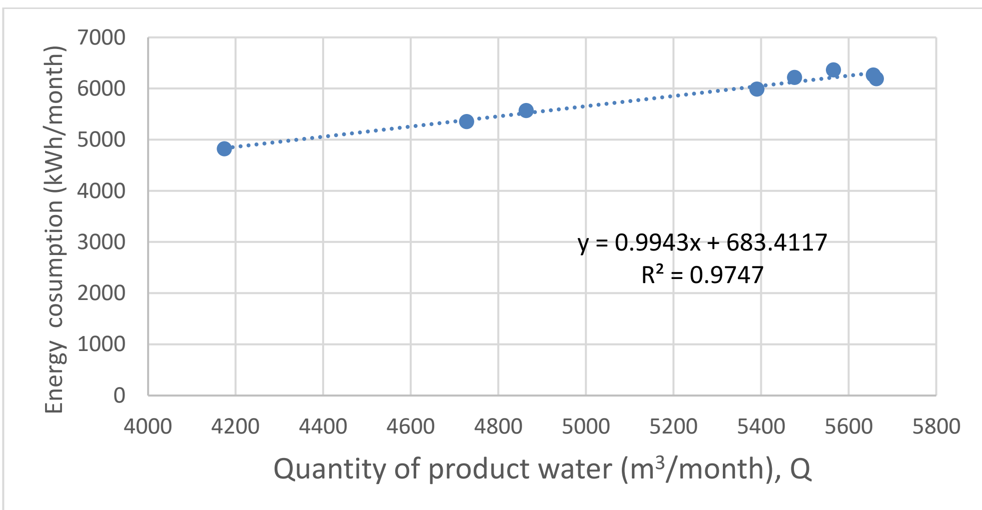

Fig. 8: Baseline model for the monthly energy and water data for the year 2021 (May to December). A simple scatter diagram for one variable and regression analysis for multi-variables for the monthly energy and water data for the year 2021

measurements at the HU BWRO plant. Data were obtained from the installed fixed meters within the BWRO station; the power and energy measurements were obtained from the power and energy analyzer. There was a challenge faced during the measurements while operating the BWRO station to take the required measurements due to the fact that the operation time was limited to the available water at the raw water storage tank due to the current shutdown of the groundwater well.

During the measurement period, the water quantities were fixed, and the pressures were found to be lower than the nominal values of the pumps due to the usage of the VFDs. The following readings in Table 6 show the power consumption. These values consist of two parts: the consumption of the

Table 4: Summary of the field measurements at the HU BWRO station

No.	Meter	Parameter	Unit	Reading 1	Reading 2	Reading 3	Reading 4
1	Feed flow meter	Flow rate	m^3/h	0	62.98	62.5	0
2		Totalizer	m^3	164,750.13	164,753.08	164,767.05	164,802.28
3	Reject flow meter	Flow rate	m^3/h	0	9.03	8.8	0
4		Totalizer	m^3	21,336.11	213,36.74	21,338.74	21,343.75
5	Mixing flow meter	Flow rate	m^3/h	0	11.47	28.94	0
6		Totalizer	m^3	93,272.39	93,272.57	93,276.9	93,293.58
7	Treated flow meter	Flow rate	m^3/h	0	0	80.31	0
8		Totalizer	m3	247,180.66	247,180.66	247,181.92	247,223.09
9	Quality of raw water	EC	µS/cm	2.352	2,709	2,682	5.016
10		TDS	ppm	1	1,138	1,139	2
11		pH	unity	7.49	7.95	7.96	5.33
12		TEMP	deg C	12.3	19.2	19.3	17.4
13		CL_2	mg/L	0	0.01	-0.01	0
14	Quality of product water	EC	µS/cm	1.481	1.485	1445	1659
15		TDS	ppm	1	1	545	704
16		pH	unity	8.75	8.75	8.73	8.74
17		TEMP	deg C	12.2	12.2	16.6	17.9
18		CL_2	mg/L	-0.084	-0.082	0.366	0.522

Table 5: Measurements Records at the BWRO station at the HU

Date	01-Sep-2022	Sample time	2:22 pm
No.	Reading	Unit	Value
1	Raw water quantity	m^3/h	63
2	Desalinated RO water quantity	m^3/h	54
3	Final treated water quantity	m^3/h	81
4	Rejected water quantity	m^3/h	8.9
5	Water pressure before protection filters	bar	3.2
6	Water pressure after protection filters	bar	2.8
7	Water pressure of stage #1	bar	9.9
8	Water pressure of stage #2	bar	7.5
9	Water pressure before inter-stage pump	bar	6.5
10	Water pressure after inter-stage pump	bar	9.7
11	Rejected water pressure	bar	9.4
12	Desalinated RO water pressure/stage #1	bar	0.5
13	Desalinated RO water EC	µS/cm	988
14	Final treated water EC	µS/cm	1,658
15	Final treated water excess chlorine	mg/L	0
16	pH	unity	8.7

Table 6: Active total power measurements from the BWRO station at the HU

Basic power		Power with TP15 kW off		Power with TP15 kW	
Reading #	Power (W)	Reading #	Power (W)	Reading #	Power (W)
Average	5,216.67	Average	32,145.79	Average	47,166.52
Net average power without basic loads (W):					41,949.86
Net average power without basic loads and treated water pump (W):					26,929.12
Measured specific energy with respect to treated water 83 m^3/h (kWh/m^3):					0.505
Measured specific energy with respect to RO water 67 m^3/h (kWh/m^3):					0.402

treated water pump from the 50-m^3 tank to the 1500-m^3 reservoir and the basic load for the BWRO station, including the ACs, internal lighting, etc. The average net power value was 47,166.5 W, while the maximum average recorded value was 50,760 W and the maximum specific energy was 0.625 kWh/m^3. These

Table 7: Comparison of specific energy consumption and cost of product water with similar desalination plants in the MENA countries.

Country	Specific Energy Consumption (kWh/m^3)	Cost of desalinated water USD/ m^3	Sources
Morocco	4.0	1.0	Kettani and Bandelier, 2020
Saudi Arabia	3.5–3.75	0.825	Sayed *et al.*, 2022
Bordering the Red and Mediterranean Seas	2–4	1.52–1.74	Maftouh *et al.*, 2023
Jordan	2.7–5.6	0.60–1.18	Bdour *et al.*, 2022
India	4.0	2.4–3.6	He *et al.*, 2020
Egypt	4–5	1.25	Shouman *et al.*, 2015
Palestine	2.33	0.95	Hussam H. A., 2013
Hashemite University, Jordan	0.62	0.36	The current study

details are shown in Table 6. Given that the average basic load before operating the BWRO station was 5,216.67 W, the treated water pump with a nominal power of 15 kW was not operational at the beginning of the operation of the BWRO station because the treated water tank was empty.

Based on the above results, the net average power without basic loads is 41,949.855 W, while the net average power without basic loads and a treated water pump is 26,929.123 W. The measured specific energy with respect to treated water (83 m^3/h) is around 0.505 kWh/m^3, while the measured specific energy with respect to RO water (67 m^3/h) is around 0.402 kWh/m^3. The above findings reveal a highly efficient BWRO plant, opposite to the first assumption of a 1.2 kWh/m^3 specific energy. This could be justified due to the following reasons: 1) The use of high-efficiency reverse osmosis (RO) membranes (low energy membranes), 2) the use of VFDs for all pumping units, and 3) the blending of the desalinated water product with a portion of the raw water using a small pump. The raw and treated water tanks are concrete tanks that are adjacent to each other. The idea of the cancellation of the mixing pump may require an adjustment and modification to the BWRO station, which seems to be an infeasible option for a 4-kW pump versus the required investments and works to cancel the mixing pump. By comparing the findings of the current study with other desalination plants in the Middle East and North Africa (MENA) countries regarding specific energy consumption values and cost of desalinated water, the results in Table 7 reveal that the HU-PV BWRO plant exhibits exceptional performance in terms of energy costs, energy efficiency, and energy consumption. This achievement can be attributed to effective plant management, meticulous operation practices, and the integration of renewable energy sources to power the plant. The findings of this comparison highlight the potential for substantial cost reduction and enhanced sustainability, achieved through lowered greenhouse gas emissions. By integrating renewable energy, the economic feasibility of desalination can be greatly improved, contributing to both environmental preservation and economic efficiency. A noteworthy aspect of this study is its recognition of the synergy between brackish water desalination and groundwater utilization. By considering the integration of these water sources, this study offers insights into how the pressing water scarcity issue in Jordan can be alleviated. This underscores the pivotal role that desalination can play within a comprehensive water management strategy, providing a multifaceted solution to water shortage challenges.

Regarding the comparison of the technology used, a multi-stage flash distillation (MSF) brackish water desalination technology tends to be less energy-efficient compared to advanced RO with an energy recovery device. The requirement for heating and evaporation at varying stages consumes more energy, leading to higher operational costs. Also, RO technology offers a more convenient and effective solution for various capacities (Tayyeban *et al.,* 2022). Contrarily, there are potential barriers and limitations that could hinder the widespread adoption of the proposed strategies for brackish water desalination energy production. These barriers are important to consider, as they provide a more comprehensive understanding of the challenges that need to be addressed to make the strategies viable. Some common barriers are 1) the high initial cost due to implementing advanced membrane technology, energy recovery devices, and solar energy; 2) low electricity tariff structures and fragmented energy policies; and 3) technical challenges and operational complexity, which might require trained and specialized expertise.

Energy recovery by hydropower micro-turbines.

Another possible energy efficiency option is to recover energy from the brine water for the 8-m^3/h flow and around 11 bar excess pressure. The estimated power recovered by this figure is around 1.6 kW, which translates to an estimated savings of around 3–4%. This was calculated using the following hydropower using Eq. 1 (Blackburn, 1993).

$$P = mg * Hnet * \eta \qquad (1)$$

Where

P: Power, measured in Watts (W).

m: Mass flow rate in kg/s (numerically the same as the flow rate in liters/second because 1 liter of water weighs 1 kg).

g: TGravitational constant, which is 9.81 m/s^2.

H_{net}: Net head, which is the gross head physically measured at the site less than any head losses. Head losses can be assumed to be 10%, so H_{net}=H_{gross} x 0.9.

η: The product of all components' efficiencies, which are normally the turbine, drive system, and generator.

For a typical small hydro system, the turbine efficiency would be 85%, the drive efficiency would be 95%, and the generator efficiency would be 93%, so the overall system efficiency would be calculated as follows:

0.85 x 0.95 x 0.93 = 0.751 (i.e., 75.1%)

If the gross head is relatively low, the gross head is 110 meters (11 bar). As in this study, the gross head is considered relatively low, a turbine could take a maximum flow rate of 8 m^3/h (0.0022 m^3/s), and the maximum power output of the system would be the gross head converted into the net head, multiplied by 0.9 as follows:

H_{net} = H_{gross} x 0.9 = 110 x 0.9 = 99 m

Then, the flow rate in m^3/s is converted into liters/second by multiplying it by 1,000 as follows:

0.0022 m^3/s = 2.222 *l/sec*

Knowing that 1 liter of water weighs 1 kg, kg/s is the same numerically as the flow rate in liters/second (in this case, 2.22 kg/s). Then, the hydropower power is determined as follows:

P = 2.22 x 9.81 x 99 x 0.751 = 1,621 W = 1.621 kW

An additional avenue for improving energy efficiency is the potential recovery of energy by addressing poor power quality issues. After identifying and measuring the possible energy waste due to poor power quality, it was determined that the maximum power that can be recovered in our case falls within the range of 0.8–1.6 kW. This recovery could lead to estimated savings of up to 3%. It is important to note that for both energy recovery processes through hydropower micro-turbines and curing poor power quality issues, comprehensive studies are necessary to assess their feasibility and the potential energy savings they may offer. Such studies will provide a better understanding of the practicality and effectiveness of these options in achieving significant energy efficiency improvements.

Techno-economic modeling and financial analysis results

Regarding the feasibility of the HU BWRO desalination configuration, including the on-grid PV BWRO with a 100% operating capacity of 1,992 m^3/d, the capital investment of constructing this plant was 1,393,935 United States dollars (USD). The average maintenance and operational costs equal 54,280 USD/year, and the normalized initial and running costs per kWp PV installed capacity are 26,400 USD and 1,028 USD per year. For the PV system alone, the capital investment was approximately 47,887 USD for the 52.8-kWp on-grid PV system, while the estimated average operation and maintenance cost is estimated at 14 USD/kWp/year. Based on the above data, the feasibility of the plant was investigated for the following two scenarios:

1. Techno-economic feasibility, including only savings from PV system (PV scenario).

With solar PV system capacity, system cost, electrical consumption, estimated energy to be generated by the solar PV system, % of energy bill coverage by the solar PV system, and solar system productivity, the total energy savings over 25 years is 2,193,198 kWh (727,407 USD). The system costs were based on

Table 8: Financial parameters for techno-economic modeling of HU PV-BWRO plant feasibility (Self-financing with O and M deduction)

No.	Parameter	52.8 kWp on-grid PV system	BWRO+52.8 kWp PV
1	System capacity-kWp or m^3/h	52.8	83 m^3/h
2	Energy yield-kWh/kWp	1,814	1,814
3	System cost (CAPEX)-USD/kWp	907.04	26,400
4	Investment CAPEX [USD]	(47,891.55)	-1,393,935
5	Water yield-m3/day	1,992	1,992
6	Energy/water cost savings [USD/kWh or USD/m^3] – energy/water tariff	0.36	1.76 USD/m^3
7	O and M cost oPEX [USD/y]	14.08	1,026
8	Simple payback period (SPB)	1.4	1.1
9	Net present value (NPV) [USD]	724,304.23	29,603,232
10	Internal rate of return (IRR)	70%	89%
11	Total costs over systems life (CAPEX + OPEX) [USD]	(66,483.10)	-1,953,164
12	Total energy production over 25-year project life span (kWh)	2,193,198	2,193,198
13	Level zed cost of energy (LCoE) [USD/kWh]	0.03	1.25
14	Price to current tariff price (% kWh)	8%	348%
15	Positive benefit-cost ratio (B/C ratio)	13.26	15.69

the constructed plant considering all costs such as solar PV system components, preconstruction, civil, electromechanical works, O and M, duties, and all related construction costs.

2. Techno-economic feasibility, including the savings from the PV system and reduced water demand costs (BWRO+PV scenario).

This scheme seemed to be the most probable financing model for the project and was used to proceed with the financial analysis of the feasibility of the project. Desalinated water production capacity, the solar PV system's capacity, system costs, electrical consumption, estimated water to be produced by the BWRO system, estimated energy to be generated by the solar PV system, water tariff, electricity tariff, % of energy bill coverage by the solar PV system and solar system productivity. The system's costs were based on the constructed plant considering all costs, such as RO, solar PV systems components, preconstruction, civil, electromechanical works, transmission lines, O&M, duties, and all related construction costs. The financial and cash flow analysis for this plant is summarized in Table 8, representing the base scenario (self-financing) by the plant owner (the HU).

The results shown in Table 8 suggest that both scenarios are financially feasible, but the BWRO+PV scenario appears to have more favorable financial outcomes, including a higher net present value (NPV), internal rate of return (IRR), and positive benefit-cost (B/C) ratio. The PV scenario has a payback period of 1.4 years, while the BWRO+PV scenario has a slightly shorter payback period of 1.1 years. Also, the PV scenario indicates a positive NPV of 724,304 USD, whereas the BWRO+PV scenario shows a significantly higher positive NPV of 29,603,232 USD. Also, both scenarios demonstrate favorable IRR values (70% for the PV scenario and 89% for the BWRO+PV scenario). Also, by utilizing renewable solar PV energy sources to power the BWRO plant, a considerable amount of GHG reductions, mainly CO_2 reductions, were achieved, resulting in an estimated CO_2 reduction of around 1,289,600 kg during the 25-year project lifetime.

CONCLUSIONS

In conclusion, energy efficiency plays a crucial role in the success and sustainability of desalination technologies. Energy considerations are intricately linked with every aspect of the planning, management, and operation of water desalination. The strategic planning phases include critical decisions, such as selecting energy-efficient desalination tools and optimizing the plant's energy efficiency during the initial design stages. Efficient system design, advanced process control, and proactive maintenance practices contribute to minimizing energy consumption and maximizing plant performance. Addressing energy efficiency throughout all stages of the desalination process is crucial to achieving cost reductions, reliability, and environmental sustainability. Also, integrating energy-efficient measures into plant operations not only reduces operational costs but also minimizes the environmental footprint of desalination technologies. This study involved a comprehensive evaluation of the sustainability of the HU-PV BWRO desalination plant, focusing on several key dimensions. Addressing the energy efficiency challenge remains a significant hurdle in desalination technology due to high energy consumption. Using energy-efficient technologies, such as reverse osmosis membranes and energy recovery devices, yields promising results by substantially decreasing energy consumption and reducing the energy footprint of desalination plants. Also, the economic implications of integrating solar energy sources significantly reduce the cost of desalination and make the desalination technology more sustainable by lowering GHG emissions, contributing to both environmental preservation and economic efficiency. Furthermore, brackish water desalination in combination with groundwater offers insights into alleviating the pressing water scarcity in Jordan and highlights the importance of integrating desalination into a broader water management strategy. It was found that the net average power for the BWRO plant was 41,949.855 W, while the net average power for the BWRO plant without including the treated water pump was 26,929.123 W, and the measured specific energy with respect to treated water of 83 m^3/h was around 0.505 kWh/m^3, while the measured specific energy with respect to RO water of 67 m^3/h was around 0.402 kWh/m^3. The above findings reveal that the BWRO station is highly efficient, which is mainly attributed to the use of high-efficiency RO membranes (low-energy membranes) and the employment of VFDs for all pumping units. A potential option for improving energy efficiency is to recover energy from brine water. The estimated power recovered is around 1.6 kW, representing a potential energy savings of approximately 3–4%. Another opportunity to enhance energy efficiency is to address poor power quality issues and recover wasted energy. Measurements revealed that the maximum power that can be recovered by resolving these issues falls within the range of 0.8–1.6 kW, translating into an estimated savings of up to 3%. The installation of renewable PV energy for the BWRO plant presents further opportunities for optimization. The following steps are recommended to maximize the use of renewable energy: 1) Increasing the number of PV panels to improve the DC/AC ratio and enhance energy production from the solar PV system; 2) adjusting the operation time of the BWRO to coincide with the sun's peak hours, typically around noon, to capitalize on the highest solar energy availability; and 3) frequently and efficiently cleaning PV modules to ensure their optimal performance and energy generation. By implementing these measures, the BWRO plant can enhance its energy efficiency, reduce energy wastage, and improve the overall sustainability of its operations. The feasibility of the HU PV-BWRO plant was investigated, and the results indicate a fast payback period of up to 1.1 years. This represents the base scenario of the self-financing scheme by the project owner (the HU). The results reflect the good feasibility of the project and an acceptable rate of return. Utilizing clean solar PV energy to power the BWRO plant led to considerable reductions in GHGs, mainly CO_2; the estimated amount of CO_2 savings during the project lifetime is around 1,289,600 kgCO_2. As advancements in desalination continue, the integration of solar energy sources shows promise in further enhancing energy efficiency and sustainability. An additional comprehensive analysis and industrialization of these technologies are essential to optimizing their performance and cost-effectiveness. The findings of this research contribute to a more environmentally friendly and economically viable desalination sector, which is of paramount importance in addressing global water scarcity concerns.

AUTHOR CONTRIBUTIONS

A. Bdour performed the research work plan, data interpretation, and manuscript edition. A. Hijab performed the field measurements and research experimentation and prepared the manuscript text. L. Almakhadmeh helped with the data analysis and organized the manuscript text. M. Hawa performed the literature review and helped in field measurements and research experimentation.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS	DEFINITION
%	Percent
AC	Air conditioning
B/C ratio	Benefit-cost ratio
BWRO	Brackish water reverse osmosis
CAPEX	Capital expenditure
CL_2	Chlorine
CO_2	Carbon dioxide
DC/AC	Direct current to alternating current ratio
EA	Energy auditing
EC	Electrical conductivity
ECMs	Energy conservation measures
GHGs	Greenhouse gases
HCL	Hydrochloric acid
HPP	High-pressure pump
HU	Hashemite University
IRR	Internal rate of return
kW	Kilowatts
kW/m^3	Kilowatts per cubic meter
kWh	Kilowatt-hours
kWh/m^2	Kilowatt-hours per square meter
kWp	Kilowatt peak (a measure of solar panel capacity)
LCoE	Levelized cost of energy
LPP	Low-pressure pump
m^3	Cubic meter
m^3/d	cube meter per day (
m^3/h	Cubic meters per hour
MEMR	Ministry of Energy and Mineral Resources
MENA	Middle East and North Africa
MED	Multi-effect distillation
MSF	Multi-stage flash distillation
MW	Megawatts
NPV	Net present value
OH	Operating hours
O&M	Operation and maintenance
OPEX	Operational expenditure
pH	Potential of hydrogen
PV	Photovoltaic
RO	Reverse osmosis
SEC	Specific energy consumption
SWOT	Strengths, weaknesses, opportunities, threats
TDS	Total dissolved solids
TEMP	Temperature
TW	Treated water
USD	United States dollars
VFDs	Variable frequency drives
Y	Year

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SPECIAL ISSUE: Eco-friendly sustainable management
CASE STUDY

Sustainability index analysis of organic fertilizer production from paunch manure and rice straw waste

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ABSTRACT

BACKGROUND AND OBJECTIVES: Substantial quantities of livestock waste and organic pollutants, such as nitrogen and phosphate, which pose environmental risks are generated from agriculture activities. A combination of paunch manure and rice straw is used as organic fertilizer. Therefore, this study confirmed sustainability of organic fertilizer from paunch manure and rice straw waste.
METHODS: Data were collected through focus group discussions and the closure of questionnaires which contained 29 attributes related to environmental, economic, social, and technological dimensions. The data collected was analyzed using the Multidimensional Scaling method, Rapfish software, and Monte Carlo analysis to ascertain the level of sustainability status and leverage attributes, and examine scoring errors and variations.
FINDINGS: Sustainability index for organic fertilizer production was 74.55 percent. The result showed that the method contributed to the growth of sustainability in various operational phases, including the processing and commercialization of organic fertilizer. According to analysis of the four dimensions, the environmental dimension held the highest leverage value at 90.1 percent, followed by social, economical, and technological dimensions at 70.50 percent, 63.69 percent, and 73.93 percent, respectively. This study identified seven leverage attributes that are very influential to sustainability of organic fertilizer production. These include water use and raw material efficiency, potential business scale increase, market absorption, the potential for public unrest, the manager or worker level of expertise in the manufacture of organic fertilizer as well as the process used to determine its quality and output.
CONCLUSION: The proposed inquiry conducted within the context of this study identified the pivotal factors that influenced organic fertilizer supply framework as the quality, quantity, and market absorption of organic production. As a result, the o use of agricultural waste as a valuable addition to a perfect social, economical, and technological development system needs to be encouraged. The study is significant because it offered information about the viability of producing organic fertilizer in Indonesia, which the government and other stakeholders may use to guide their policies and programs.

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INTRODUCTION

The intensive use of inorganic fertilizer in agriculture causes numerous problems, such as irreversible health and environmental pollution. However, organic farming offers a potential solution because it has the capacity to reduce or even eliminate the harmful impacts of inorganic fertilizer on the environment and human health (Sharma and Chetani, 2017; Samimi *et al.,* 2023). By relying on organic sources, this farming type is one of the sustainable agricultural strategies to produce safe, healthy, and cost-effective food, including restoring soil fertility (Timsina, 2018) and mitigating climate change (Nugroho *et al*., 2023). While challenges related to composting of agricultural waste persist due to environmental concerns, experts are actively developing alternative solid waste management methods (Weekes *et al.,* 2021; Le Dinh *et al.* 2022; Sivakumar *et al.* 2022; Maphosa and Maphosa, 2022). These methods encompass a wide array of organic fertilizer raw materials sourced from agricultural and non-agricultural waste, which have gained endorsement from the solid waste industry over the past two decades for treating agricultural waste (Brotosusilo *et al.* 2022; Zaman *et al.* 2021). Organic substances, including protein and carbohydrates, such as starch, cellulose, hemicellulose, lignin, and organic acids, vary in the composition of agricultural waste (Suhartini *et al*., 2022). This diversity underscores the need for affordable and environmentally friendly alternatives (Roy *et al*., 2023), particularly as the costs associated with processing agricultural waste for environmental management are considerable and of global concern (Aziz *et al*., 2022; Ghazali *et al.,* 2021; Samimi and Mansouri, 2023). Compositing has emerged as a pivotal method due to its multifaceted benefits in managing agricultural waste. It effectively reduces waste volume and weight, produces nutrient-rich fertilizer that enhance soil quality, and provides a safe, stable, and advantageous practice (Roy *et al*., 2023). From sustainability standpoint, the innovative use of agricultural and food waste for biogenic nanoparticle synthesis depicts a novel method for repurposing resources aligned with waste-to-wealth principle (Pushparaj *et al*., 2022). Preliminary studies elucidating the efficacy of aquatic plants (Samimi and Shahriari Moghadam, 2018) and microorganisms (Samimi and Shahriari Moghadam, 2020), specifically Lemna minor and Chlamydomonas incerta, have proven their capacity to remediate organic pollutants (Samimi and Shahriari Moghadam, 2021). Such bio-remediation aligns with improved water quality standards and offers a sustainable avenue for production of organic fertilizer (Kamyab *et al*., 2017). Composting food waste is an economically and environmentally viable strategy. This becomes evident when considering the potential to reduce landfill-bound solid waste and significantly curb GHG emissions by 47 percent (%) and 90%, respectively. These tangible benefits underscore the importance of integrating viable waste management practices into contemporary sustainability indices Kamyab_2015_b. Both rice straw and cow dung are potential raw materials for organic fertilizer. In an agriculturally dependent nation like Indonesia, where rice is a staple food, farmers use their farm produce and livestock as a source of food and revenue. The extensive rice harvest area spanned approximately 10.45 million hectares, with production of 54.75 million tons of dry-milled grain (GKG) in 2022, accentuated the need for resource optimization (BPS, 2022). Supposing the residual from rice cultivation, estimated at 54.75 million tons of straw waste aligned with grain production, poses an environmental challenge. The removal of rice straw after harvest tends to reduce biogenic methane emissions. It can inadvertently lead to increased nitrous oxide and carbon dioxide emissions due to intensified fertilizer use for optimal rice yields (da Silva *et al.,* 2021). Crop residues such as biomass offer both potential benefits and challenges for farmers. Unused or burnt agricultural biomass can contribute to environmental pollution (Samimi and Shahriari Moghadam, 2023; Samimi, 2024). For instance, burning residual rice straw waste is of particular concern (Singh *et al*., 2021). The transition from burning to using rice straw as animal feed led to a 13% increase in global warming potential (GWP) (Launio *et al*., 2016). Despite the complexities involved, alternative straw management plays a significant role in a broader program to mitigate the environmental impact of rice production. This would entail modifying individual habitats and the general ecology (Romasanta *et al*., 2017). In order to avoid the adverse consequences of burning as well as tap into the enormous energy potentials, it is imperative to advocate for the diverse use of straw for various benefits. Rice straw, for instance, serves multiple purposes, such as animal feed (Launio *et al*., 2016), fertilizer (Devianti *et al*., 2021), methanol production (da Silva *et al.,* 2021), energy generation (Pryshliak and Tokarchuk 2020), and the manufacture of biochar (Zhao *et al*., 2014). Apart from rice straw, another valuable source of organic matter is paunch manure produced from slaughtered ruminants, specifically in abattoirs. These facilities, where cattle are massively slaughtered for consumption, generate waste comprising a mixture of fat, protein, complex organic compounds, water, and rumen. Improper management of these wastes can result in environmental harm through the release of odors, pathogens, and disease-causing agents (Mohammed *et al*., 2019). The application of paunch manure offers various advantages, including its use as organic fertilizer, biogas energy production (Mohammed *et al*., 2019), and feed ingredients (Garcia *et al*., 2021). The use of this manure, particularly when obtained from abattoirs, is a critical step in supporting sustainable livestock production and mitigating environmental risks (Garcia *et al*., 2021). In Australia, its application on agricultural land has been proposed as a cost-effective and practical environmental option (Antille *et al*., 2018). According to Lestari *et al*. (2017), cattle paunch manure, as a digestive residue, contains organic matter and nutrients, including 2.56%, 0.15%, and 0.11% of N, P, and K. Paunch manure also contains 12.5%, 8 .1%, 38.02%, 0.37%, 0.26%, and 2,361 kcal/kg of dry matter, crude protein, crude fiber, calcium, phosphorus, and metabolic energy, respectively (Moningkey *et al*., 2020). Antille *et al*. (2018) stated that the resulting rumen contents have a fresh weight within the range of 25 and 40 kg stomachs/cow, translating to approximately 4 to 6 kg dry matter. This is consistent with a previous study, which posits the quantity of rumen content produced is estimated at 5 kg of dry matter (Kocu *et al.,* 2018). Huda *et al*. (2020) stated that the liquid rumen content of cattle contains five beneficial bacteria, namely *Pseudomonas, Cellulomonas sp., Acinetobacter sp., Lactobacillus sp.*, and *Bacillus sp*. These bacteria play a critical role in the composting process by increasing nitrogen levels, accelerating compost fermentation, promoting compound formation, and triggering the activities of microorganisms. Based on the bacterial makeup of rumen contents, it emerges as a promising source of raw material for organic fertilizer production. Lestari *et al*. (2017) stated that composting cow paunch manure as a source of organic matter improves water retention, enhances aeration and drainage as well as facilitates healthy plant root development by aiding nutrient absorption. The use of paunch manure on agricultural land proves economically prudent compared to traditional disposal methods and is widely acknowledged as an environmentally sound option. It can be managed in several ways, including 1) off-site disposal of guts and other solids, 2) on-site composting and application of materials, and (3) on-site composting, followed by off-site use (Antille *et al*., 2018). Devianti *et al*. (2021), stated that organic fertilizer possess the potential to boost land fertility sustainably while reducing environmental degradation and improving both the quality and quantity of agricultural produce. Long-term use of organic fertilizer can bolster farm productivity and counteract land degradation. In assessing the viability of agricultural waste composting, computing sustainability index using multidimensional scaling (MDS) offers an ideal method. A multivariate statistical method, also referred to as MDS, is used as a variable to assign positions to items based on their similarities or dissimilarities. MDS can convert preferences and opinions into multidimensional distances that can be interpreted scientifically. It formally refers to various statistical methods that visualize the underlying relationships between groups to condense preference data (Wan *et al*., 2021). MDS proves effective in interpreting and refining the preferences and opinions of respondents concerning organic fertilizer sustainability index theme. This method, widely used for sustainability assessment, was extensively employed in evaluating the feasibility of developing different agricultural commodities. Remarkable examples include garlic (Mar'atusholikha *et al*., 2019), cacao (Fairuzia *et al*., 2020), corn (Ariningsih *et al*., 2021), beef cattle (Kapa *et al*., 2019), dairy cattle (Mastuti *et al*., 2019), buffalo (Syarifuddin *et al*., 2022), shrimp (Pongoh *et al*., 2021), coffee (Yusuf *et al*., 2022), rice (Rachman *et al*., 2022), rice and duck (Rohaeni *et al*., 2021), oil palm (Nashr *et al*., 2021), red chili (Nuraini and Mutolib, 2023), microalgae (*Santoso et al*., 2023a), and black soldier fly (Santoso *et al*., 2023b). Given the nuanced nature of agriculture sustainability, its meaning encompasses multidimensional interpretations (Yusuf *et al*., 2022). Previous studies on sustainability used ecological, economic, social, technological, and institutional dimensions, while others delved into ethics, marketing, and political aspects during analysis. There exists divergence in the opinions held by these studies regarding the number and selection of dimensions to use. In this study, a four-dimensional framework encompassing environmental, economic, social, and technological facets aimed to provide practical insights and considerations for decision-makers vested in sustainable development. It is hypothesized in the present study that the use of rice straw and pig dung as organic fertilizer will lessen pollution and enhance soil conditions. The practical MDS method offers valuable information to assist decision-makers in organic fertilizer industry, particularly concerning waste management. The present study seeks to achieve the following objectives 1) identify sustainability index dimensions, 2) calculate sustainability index across environmental, social, economic, and technological dimensions, and 3) identify the critical factors influencing organic fertilizer production system. It also evaluates the viability of organic fertilizer production supply system. This study which was conducted in the Environmental and Sustainable Agribusiness Systems study group at the National Research and Innovation Agency, Indonesia, contributes to understanding viable practices in agriculture.

MATERIALS AND METHODS

Materials

The present study focused on the combination of rice straw waste and pound manure as the core material for investigation. Rice straw waste is considered a promising source of organic fertilizer raw materials, with its detailed contents shown in (Tables 1) and (Table 2). Meanwhile, the chemical composition of paunch manure is shown in (Table 3).

The combination of paunch manure and rice straw produces quality organic fertilizer. This is supported by Ratnawati *et al.* (2018), that the combination of paunch manure and rice straw produces organic fertilizer in accordance with the established quality standards. This is characterized by high phosphorus (P) and potassium (K) macronutrient values, a balanced carbon per nitrogen (C/N) ratio, and an optimal potential of hydrogen (pH) level. Furthermore, it was found that the best combination was 40% paunch manure and 60% rice straw produced by organic fertilizer with a pH specification and C/N ratio of 6.79 and 15, including macronutrients P and K of 8.35% and 9.72%, respectively. This formulation meets the established organic fertilizer quality standards, encompassing a pH and C/N ratio within the range of 4 to 9 and 15 to 25 and a minimum macronutrient content of 2% for both P and K.

Organic materials from rice straw waste and livestock manure (such as stomach manure) offer significant benefits in overcoming fertilizer requirements and boosting soil fertility. These organic matters contribute to effective fertilization in the following ways (Mclllfaterick, 2017):

a. Organic matter contained in rice straw and rumen contents (livestock manure) contributes significantly to enhancing soil structure. This is achieved by effectively binding soil particles into larger aggregates, thereby facilitating enhanced air

Table 1: Chemical composition of rice straw waste

No.	Nutrient elements	Composition (%)		
		(Ngi *et al.*, 2006)	(Sarnklong *et al.*, 2010)	(Poripolli *et al.*, 2016)
1	DM	92.8	96.3	90.6
2	CP	4.2	-	4.2
3	CF	35.1	-	-
4	NDF	69.1	73.0	73.2
5	ADF	42.4	41.6	44.9
6	ADL	4.8	4.8	3.2
7	EBSi	-	4.3	-
8	Ash	18.1	12.1	-
9	Ca	0.29	1.58	-
10	P	0.09	0.12	-
11	Na	0.27	0.13	-
12	K	1.8	0.27	-

Table 2: Nutrient contents of several sources of compost raw materials (Lemma and Abera, 2020)

No.	Sources raw materials	Moister (%)	Total nitrogen (%)	Carbon/ Nitrogen ratio	P available (mg/kg)	K available (mg/kg)
1	Paunch manure	77.28	3.03	10.31	1,523	597.7
2	Cattle manure	65.67	2.01	14.38	1,329	927.8
3	Paunch manure + wheat straw	79.18	1.58	16.26	1,226	682.3
4	Cattle manure + wheat straw	69.71	1.51	17.51	1,023	988.0
5	Paunch manure + cattle manure + wheat straw	76.10	2.08	14.34	1,408	933.0

Table 3: Chemical composition of paunch manure

No	Nutrient elements	Composition (%)		
		LAPTIAB-BRIN	Dowd *et al.* (2022)	Garcia *et al.* (2021)
1	MC	9.85	-	-
2	CP	7.59	11.30	-
3	Crude Fiber	30.35	-	-
4	Crude Fat	5.14	2.58	-
5	NDF	63.12	63.65	75.3
6	ADF	52.28	38.30	41.9
7	ADL	19.58	8.12	33
8	Ash	9.85	8.50	-
9	Carbohydrate	67.15	53.73	-
10	Ca	-	0.46	-
11	P	-	1.17	-
12	TS	-	15.84	-
13	N	-	1.59	-
14	Cellulose	-	33.65	-
15	Hemicellulose	-	28.80	-
16	VS (% of TS)	-	92.90	-

and water circulation within the soil.

b. Organic matter contains various nutrients such as Nitrogen, Phosphorus, and Potassium. When it is decomposed by microorganisms in the soil, these nutrients are progressively released into the soil, ensuring a gradual and efficient supply.

c. Organic matter can retain moisture in the soil, helping it stay moist for a longer period of time and reducing water evaporation.

d. Organic materials serve as nourishment for microorganisms in the soil. These microorganisms facilitate the decomposition of organic matter and production of plant-friendly compounds. Higher microbial activity also has the potential to enhance overall soil fertility.

e. By integrating organic matter into the soil, agriculture can reduce its dependence on synthetic chemical fertilizer. This tends to reduce the environmental footprint caused by its excessive use.

f. Organic matter increases the water storage capacity of the soil, this helps keep plants hydrated during dry weather conditions and reduces the risk of shortages.

The conversion of plant residues into organic matter involves a natural decomposition process that produces compounds beneficial to the soil and ecosystem. This intricate process relies on the collaborative efforts of microorganisms such as bacteria, fungi, and worms, working harmoniously to decompose these organic materials. However, this transformation is significant as it reduces waste, enhances soil quality, and provides essential nutrients for plant growth. Several methods are used to achieve the conversion of plant residues into organic matter. These methods include natural composting, making compost, vermicompost, liquid fertilizer, and fast composting using bacteria or microorganisms.

Study procedure

Focus Group Discussions (FGDs) were used to analyze the survey data, involving experts in solid waste, organic fertilizer, and business domains. These individuals were selected based on their qualifications, requiring a minimum of five years of experience in organic fertilizer production and management. The primary goal of the FGDs was to evaluate the current business environment and the available resources for organic fertilizer production at the study site, providing essential insights for formulating dimensions and sustainability attributes. The present study incorporated a total of 29 attributes organized into four dimensions, namely environmental, economic, social, and technological. A questionnaire was crafted to quantify these dimensions and attributes, using a Likert scale for response options. Expert participants were assigned scores of 0, 1, and 2 to indicate poor, average, and good responses.

Data analysis

Data analysis was performed using MDS alongside the rapid appraisal for organic fertilizer method (Rap-fertilizer). This method was adopted and developed from the rap-fish (rapid appraisal for fish) method and modified to assess sustainability of organic fertilizer production. Furthermore, the following stages determine this evaluation process (Lloyd *et al.*, 2022; Pitcher and Preikshot, 2001).

1) The present study assessed sustainability by examining four dimensions, each comprised of 29 attributes.

2) Perform a structured assessment of the attributes through scoring. The scores assigned to the attributes form an X matrix (n x p), where n is the number of regions and their reference points, and p signifies the number of attributes used. The scores were then standardized for each attribute using Eq. 1 (Borg *et al.*, 2018).

$$X_{ik}sd = \frac{X_{ik} - X_k}{s_k} \tag{1}$$

Where;

$X_{ik}sd$ = the i-th regional standard score (including reference points) = 1, 2, ..., n for each k-th attribute = 1, 2, ..., p

X_{ik} = the i-th standard score (including reference points) = 1, 2, ..., n for each k-th attribute = 1, 2, ..., p

X_k = the mean score on each k-th attribute = 1, 2, ..., p

S_k = the standard deviation of scores for each k-th attribute = 1, 2, ..., p

The shortest interval from the Euclidian distance was calculated using Eq. 2. Subsequently, this data was projected into a two-dimensional Euclidian space (d_{12}) using the regression formula in Eq. 3. The ALSCAL algorithm facilitated the regression process, with iterations aimed at setting the intercept value in the equation to zero (a = 0). This transformation led to the conversion of Eq. 4 (Borg *et al.*, 2018). The repetition process stopped when the stress (S) value was <0.25, which was obtained using Eq. 5 (Borg *et al.*, 2018).

$$d = \sqrt{\left(|x_1 - x_2|^2 + |y_1 - y_2|^2 + |z_1 - x_2|^2 + \ldots\right)} \tag{2}$$

$$d_{ij} = \alpha + \beta\delta\beta_{ij} + \varepsilon \tag{3}$$

$$d_{12} = bD_{12} + e; \tag{4}$$

$$s = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i\sum_j\left(d_{ijk}^2 - o_{ijk}^2\right)^2}{\sum_i\sum_j o_{ijk}^4}\right]} \tag{5}$$

3) Conduct an assessment to determine sustainability index and its associated status. The categorization of sustainability status for organic fertilizer production is delineated by distinct index ranges, 0.00 to 25.00 (not sustainable), 25.01 to 50.00 (less sustainable), 50.01 to 75.00 (moderately sustainable), 75.01 to 100.00 (highly sustainable), as validated by Rachman *et al.* (2022).

4) Conduct a sensitivity (leverage) analysis to determine the main attributes that strongly influence sustainability of organic fertilizer production in farming. This analysis prioritized changes in the root mean square (RMS) ordination on the x-axis. However, assuming the RMS has a significant value, it depicts that the role of this attribute is becoming more prominent in shaping sustainability status (more sensitive).

5) Perform Monte Carlo analysis using the Rap-fertilizer method to estimate the random error rate in the model resulting from MDS evaluation of all dimensions with a 95% confidence level. The smaller the difference between the results of MDS and Monte Carlo analyses, the better the Monte Carlo model produced by the Rap-fertilizer method. The goodness of fit in MDS is reflected in the values of S and coefficient of determination (R^2). A low S value denotes a good fit, while the reverse is the case when its high. With the Rap-fertilizer method, a good model is indicated by an S value less than 0.25. The R^2 value close to 1 indicates that the attributes used to examine a specific dimension are reasonably accurate (Borg *et al*., 2018; Pitcher and Preikshot, 2001)

RESULTS AND DISCUSSION

Dimension and attribute

The level of sustainability in organic fertilizer production was assessed using MDS method. Furthermore, the dimensions and attributes impacting sustainability were identified by thoroughly analyzing their effects on organic fertilizer production (Lloyd *et al.,* 2022). The proposed hypothesis stated that using organic fertilizer from waste materials increases sustainability of the agricultural production system. This is achieved by identifying the most significant attribute within each environmental, social, economic, and technological dimension. Expert input from fertilizer production was used to determine the attributes of each dimension. MDS calculations were based on data obtained from a questionnaire, with a comprehensive breakdown of dimensions and attributes shown in (Table 4).

A structured method was employed in assessing the viability of composting processes for organic fertilizer production. This involved organizing the various features within each dimension into a questionnaire. Experts from relevant fields were then consulted to obtain their professional opinions on the scientific feasibility of these composting processes. The outcomes of these professional evaluations were also analyzed using MDS method and the Rapfish program. The resulting sustainability scores for each dimension are shown in (Table 5).

Various factors contribute to sustainability of organic fertilizer production, namely environmental carrying capacity, production input accessibility and procedures, product processing, marketing

Table 4: Dimensions and attributes of organic fertilizer production sustainability

Environmental	Social	Economical	Technological
1. Efficient use of materials (biodegradable) for organic fertilizer production	9. Education level of industry manager or entrepreneur	17. The productivity level of organic fertilizer	25. The easy level of adoption of organic fertilizer production system for the surrounding community
2. Efficiency in the use of chemical materials for organic fertilizer production	10. Involvement of family members in organic fertilizer industry	18. Management level of organic fertilizer production	26. The level of specialization, expertise, or skills required to manage the people's organic fertilizer industry
3. Efficiency in the use of electricity and fuel during organic fertilizer production process	11. Level of business motivation	19. Potential increase in business scale or success rate	27. Availability of organic fertilizer production facilities and infrastructure
4. Efficiency of water use during organic fertilizer production process	12. The potential for public unrest due to organic fertilizer industrial process	20. Contribution to improving the welfare of managers or workers	28. Potential for increasing technology or organic fertilizer production
5. The potential for air pollution	13. The potential for other job losses is due to organic fertilizer industry.	21. Efficient use of raw materials	29. The level of technical or method sensitivity to the quality and quantity of organic fertilizer production
6. The potential for water and land pollution	14. Managers or workers knowledge level of organic fertilizer production or environmental conservation and restoration	22. The level of ease of obtaining raw materials for organic fertilizer production	
7. Exploitation level of natural resources and land use during organic fertilizer production	15. Potential for work accidents	23. Market absorption rate of organic fertilizer production	
8. Potential spread of disease due to the existence of organic fertilizer industry	16. Potential job creation for residents	24. Contributing to the increase in substitution of organic fertilizer	

Table 5: Sustainability index outcomes for all dimensions, accompanied by data quality indices

Dimension	Index (%)	Stress	R^2(SQR)	Status
Environmental	90.1	0.135	0.947	good sustainable
Social	70.5	0.141	0.949	fairly sustainable
Economical	63,69	0.138	0.947	moderately sustainable
Technological	73,93	0.144	0.947	fairly sustainable
Average	74.55			fairly sustainable

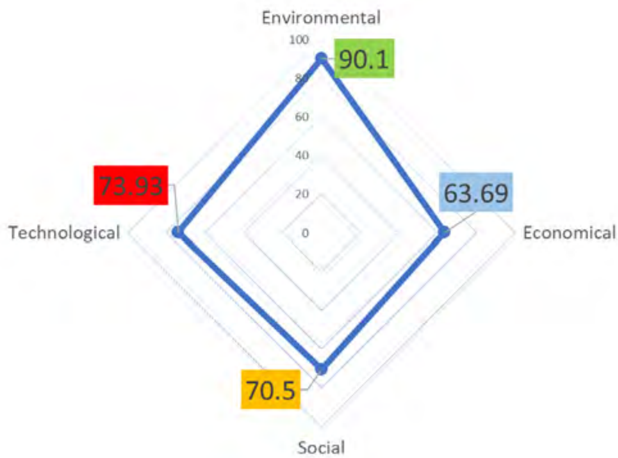

Fig. 1: The level of sustainability achieved in organic fertilizer production

strategies, and the roles of pertinent organizations. These factors along with their sustainable practices, use organic fertilizer production an economically and environmentally favorable alternative to the manufacture of conventional animal feed (Rehman *et al*., 2020). With a stress value of 0.14, equivalent to 50%, the results of MDS analysis on production of ecologically friendly organic fertilizer are shown in (Fig. 1). This shows the validity and accuracy of the four dimensions determined by the Monte Carlo test. Additionally, organic fertilizer production system yielded sustainability value of 74.55. While the economic dimension has the lowest sustainability index, it remains notably sustainable. The environmental, social, and technological dimensions fall within sustainability category, as shown in (Table 5).

Environmental dimension

Based on the MDS analysis results, 90.1% of the index value of the environmental dimension, serves as a barometer for sustainability. This commendable index status should be maintained as a positive reference point. The leverage analysis was used to identify water consumption efficiency in organic fertilization as a one-dimensional attribute that significantly influences environmental sustainability. The use of organic fertilizer inhibits soil degradation, which causes the loss of nutrients and organic matter. It also enhances the retention property of the soil, thereby protecting plants from dehydration. The positive impact extends to clay soils, where improved porosity ensures smooth drainage and prevents stagnation. These collective effects enhance soil fertility and quality, attributed to heightened organic matter content and improved water-holding capacity (Adugna, 2016). Several studies have validated the water-saving potential of using organic fertilizer. For instance, Dharminder *et al*. (2021) emphasized its water-saving properties, while El-Mageed *et al*. (2018) reported potential conservation of approximately 15%. This insight is specifically pertinent in the face of global water scarcity concerns, and agriculture is a major consumer of freshwater resources. In regions where water scarcity is prevalent, efficient usage becomes important to ensure its availability for other essential purposes. The availability of water is closely related to its quality, as deterioration of water quality

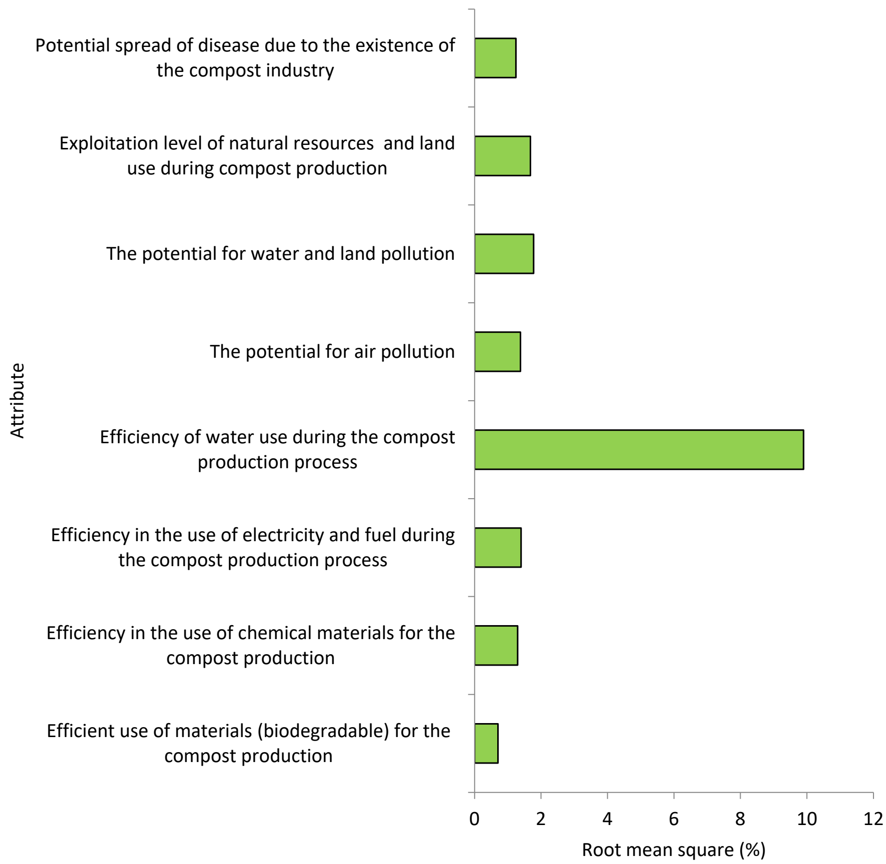

Fig. 2: Leverage of environmental attributes

limits its fitness for specific applications (e.g. drinking water). These pressures on the environment have led to a growing interest in exploring alternatives to reduce waste and the use of resources. The world need to move away from simplistic, and readily available methods to more comprehensive solutions. Embracing the principles of the circular economy and harnessing technological advancements aids to enhance sustainability and provide new market dynamics regarding the water cycle. This transition is essential to elevate sustainability efforts and effectively address evolving demands placed on water resources.

A new circular water management system that considers the various elements of the water cycle aimed at maximizing efficient usage need to be developed. Several measures need to be adopted based on the principles of the circular economy model. The initial focus rests on curbing water consumption through the redesign of products and services, coupled with the eradication of operational inefficiencies. This concerted effort led to the reduction of water usage by improving its system efficiency and resource allocation. The next step revolves around reuse, involving the establishment of a closed-loop framework for water circulation or redirecting it to alternative systems or communities. Recycling is also important for external operations. However, the ultimate goal remains centered on the restoration of natural reserves, achieved by safely reintroducing water to its original watersheds, such as rivers, lakes, and oceans. Water reuse is a concept gaining attention, viewed as an innovative way to combat its scarcity. This entails repurposing treated wastewater as a valuable resource for various non-potable applications, including irrigation, industrial processes, urban consumption, and even rejuvenating aquifers and surface waters (Plevri *et al*., 2020). The result from the experiment conducted showed that the efficiency of water use during the compost-producing process had the highest leverage value of 9.9. This observation aligns with the pressing global concern of water scarcity, exacerbated by the substantial demands of the agricultural sector. In areas with severe water scarcity, prioritizing efficient use is crucial to ensure its availability for other essential purposes. Organic fertilizer production typically includes composting and digestion, which often require water for mixing, moisture control, and maintaining optimal conditions. Improving water efficiency in these processes reduces waste and also eases the strain on its resources. Organic fertilizer production requires water because it plays an important part in the decomposition process of organic matter. It is important to consider efficient rather than excessive use of water. Adopting proper monitoring and strategic control of water use can help reduce pressure on its resources while ensuring sustainable supplies. During composting, rainwater collection and storage potentially reduces dependence on sources like boreholes and tap water. Further progress lies in adopting efficient drip irrigation, employing soil moisture sensors for precise plant hydration, and integrating automatic systems for accurate water delivery. These technological measures promote water conservation, aligning with the broader goal of environmental stewardship. The inextricable relationship between water and energy warrants attention. Processes tied to water, from extraction to treatment and distribution, require energy inputs. Inefficient water use in fertilizer production indirectly triggers increased energy consumption and associated environmental impacts. Energy demands in water-related processes tend to be minimized by optimizing efficiency, resulting in overall resource savings and reduced greenhouse gas emissions. This endeavor resonates with integrating eco-friendly technologies that harness renewable energy sources such as solar panels and wind turbines. Wastewater is usually generated by producing organic fertilizer, specifically during processing and washing. Composting generates three water forms, namely leachates, condensates, and runoff. Leachates permeate through organic matter, condensates, and runoff resulting from moisture evaporation and areas around compost heaps, including traffic zones and windrow sides (Krogmann and Woyczechowski, 2000). Inefficient water usage leads to the generation of significant amounts of wastewater, presenting considerable challenges for its proper treatment and disposal. The discharge of untreated wastewater tends to contaminate water bodies, thereby causing ecological damage and posing potential threats to human health. In order to counteract the pollution of water sources by liquid waste, it is necessary to effectively segregate and treat wastewater, thereby preventing the contamination of groundwater and rivers with harmful substances. Implementing advanced water and wastewater management practices is instrumental in addressing the pollution risks associated with producing organic fertilizer. Organic fertilizer contain essential nutrients such as nitrogen, phosphorus, and potassium. Poor water management during production process, involving either excessive usage or inadequate control, results in the infiltration of these nutrients into groundwater or causes them to run off into nearby water bodies. This situation tends to trigger eutrophication, a phenomenon where excess nutrients cause algal blooms, oxygen depletion, and disruption of aquatic ecosystems. By embracing water-efficient strategies, the leaching of nutrients and runoff could be minimized, thereby preserving water quality and the integrity of aquatic ecosystems. In view of concerns revolving around water scarcity, energy consumption, wastewater generation, pollution, and the potential for nutrient leaching and runoff, the efficiency of water usage in producing organic fertilizer emerges as a pivotal consideration for achieving environmental sustainability. Through the optimization of water practices and the adoption of efficient management, production of organic fertilizer effectively mitigates its environmental impact and actively contributes to broader sustainability goals. Rice straw is one of the most common agricultural by-products in the world, specifically in China and Southeast Asia. Farmers extensively employ it as a primary source of forage for ruminant animals, owing to its widespread availability and cost-effectiveness. The robust cellulose-hemicellulose-lignin structure of rice straw protects the biomass from being attacked by enzymes and microorganisms (Yu *et al*., 2016). This characteristic results in limited breakdown during fermentation processes resulting in low degradation during fermentation. Improving the decomposition process of straw increases the use of this abundant agricultural by-product and alleviates the shortage of high-quality forage for ruminants. The rumen of ruminants, rich in complex microbial community and cellulase system, adeptly converts lignocellulosic biomass (Xing *et al*., 2020). The best option for regulating lignocellulosic biomass involves using ruminal fluid as a biological inoculum (Liang *et al*., 2020). According to Wang *et al*. (2021), rumen juice dramatically enhanced hydrolysis and acid generation in cut grass. The factor that impacts environmental sustainability is water usage efficiency during the composting process. Microbial activities drive this procedure, and like other living organisms, bacteria need the right environment to survive and thrive. For the composting process to be successful, the bacteria need suitable nutrition, optimal humidity, pH levels, temperature, and oxygen (Seyedbagheri, 2010). For aerobic incubation, which takes place in the presence of oxygen, maintaining an appropriate humidity level to support the entire process is important. Materials with high fiber content, such as straw and wood chips, can hold higher moisture (exceeding 60%) without inducing anaerobic conditions. In contrast, materials with lesser structural strength, such as paper, grass clippings, soil, and fertilizer, tend to retain lower total moisture to prevent the development of anaerobic conditions. While the precise ideal moisture content varies depending on the pile material, a consensus typically places the optimal moisture range for on-farm composting between 50% and 60% by weight (Chen *et al*., 2011). Inadequate humidity leads to a shortage of essential water for bacteria metabolic processes, hampering their activity and causing a slowdown in the composting process. Excessive humidity means that the pores of the compost pile are filled with water rather than air, leading to anaerobic conditions. Humidity plays a pivotal role in regulating pile temperature, with drier ones experiencing more rapid temperature fluctuations than moister piles. In order to achieve the ideal moisture content, materials with different moisture content are mixed. Additional water may be added during mixing when the base material is overly dry to achieve the ideal moisture. Composting duration should be selected based on the precipitation likely to occur during the period. Moreover, seasons with high rainfall must be avoided. The precipitation problem is partially solved by covering the pile or placing it under a roof. Addressing the issue of nitrogen loss presents another consideration, this concern is alleviated by adopting mulching methods, such as covering the compost pile with either straw or plastic. Empirical observations revealed that in the absence of mulch, nitrogen loss reached 22%. This loss diminished to 13% when 25 cm of straw was used as mulch and was further curtailed to a mere 7% when a plastic layer was introduced between straw and the compost during the maturation stage. At the outset of the composting process, it is important to opt for covers that strike a balance between breathability and impermeability. Air-repellent coatings prevent aeration of the compost pile and evaporation of water. Unfortunately, this unintended consequence leads to a more anaerobic environment, exacerbating the risk of increased washout (Peigne and Girardin, 2004). Peigne and Girardin (2004) also suggested a strategic method, using straw as mulch at the start of composting and transitioning to tarpaulin when the compost is more stable during maturation. Covering the compost pile is always the best way to reduce runoff contamination because water seeping along its walls does not come in contact with manure. Opting for composting under a canopy, which offers wider coverage than a simple tarpaulin, is a more effective strategy to mitigate the adverse effects of precipitation and minimize the loss of contaminated water.

Social dimension

In the social dimension context, several influential factors come into play in the pursuit of sustainable organic fertilizer production. These factors include potential job displacement, civil unrest, and the knowledge levels of both managerial personnel and workers engaged in organic fertilizer production, as shown in (Fig. 3). According to Bartzas and Komnitsas (2020), the education level of farmers directly impacts their ability to access and effectively use modern technology for sustainable agricultural practices. The availability of technology that bolsters agricultural operations becomes crucial for these individuals to ensure the viability and lasting sustainability of their livestock enterprises. Rivero and Daim (2017) stated that technology is essential for profitable and easy-to-implement livestock production, enabling businesses to develop sustainably. This infusion empowers

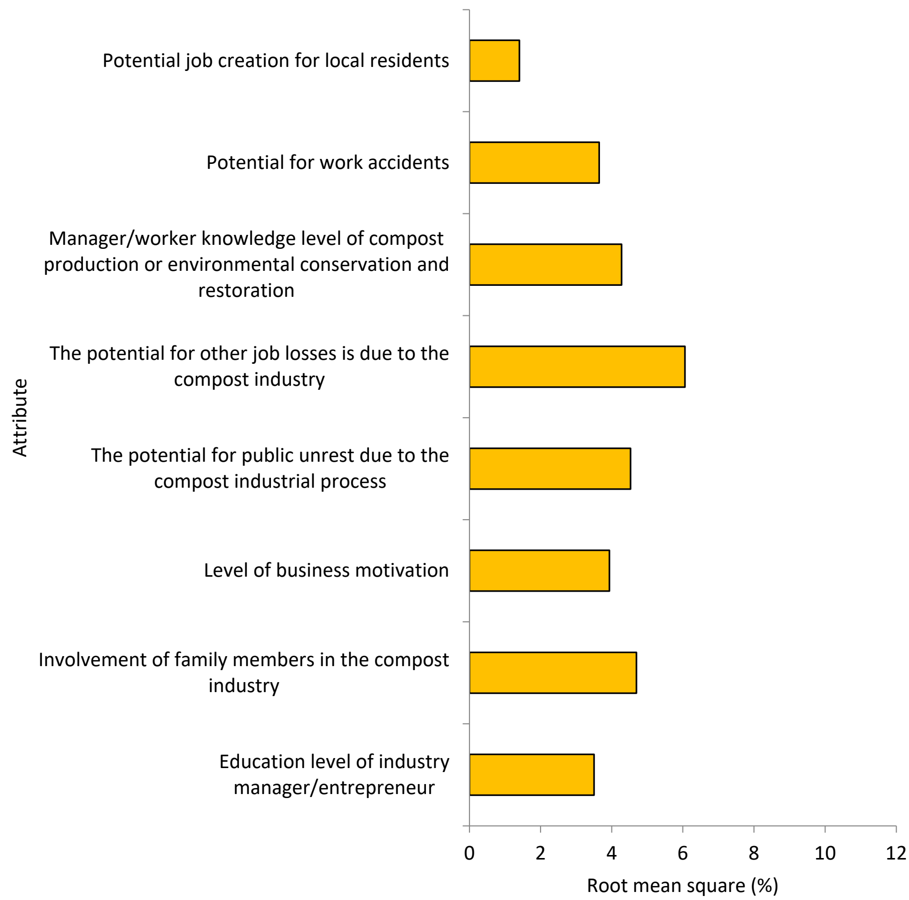

Fig. 3: Leverage of social attributes

businesses to thrive and lays the foundation for sustainable development.

In order to mitigate these adverse effects, it is important to implement regulations or adopt a family business management method. Among the various considerations, family engagement within the domestic sphere receives the highest rating, closely followed by business motives like biodiesel production, ranked second in importance. A prevailing practice within family-owned businesses involves enlisting family members to contribute to operational activities. This practice is driven by the expectation that family resources lighten the company load. The structure of family-owned enterprises often encourages managers to prioritize efficient business management. Previous studies have emphasized the importance of numerous social elements and socio-demographic traits in fostering sustainable growth and facilitating the adoption of cutting-edge farming practices and products among farmers (Pampuro *et al*., 2020). A remarkable method proposed by Sumane *et al*. 2018, revolves around establishing a multi-actor knowledge network that facilitates interactions between formal and informal sub-networks. Particularly pertinent regarding Manager/Worker knowledge levels of organic fertilizer production, this method emphasizes the value of blending insights from formal entities such as universities, study institutes, consulting services, and farmers' organizations, as well as informal sources ingrained in their daily activities. These informal networks comprise neighborhood associations, peer groups, family and personal relationships, including community connections, collectively forming a cohesive knowledge ecosystem within rural areas (Sumane *et al*., 2018). The potential job losses in other sectors due to the expansion of organic fertilizer industry have multifaceted implications for sustainability of production process. Davis (2022) stated that composting could lead to job losses in the fossil fuel industry as it reduces the demand for chemical fertilizer manufactured using non-renewable resources such as natural gas. This reduction in demand results in employment challenges for workers in the fossil fuel sector. In addition, Davis (2022) stated that implementing composting practices also causes job losses in waste management industry. As composting reduces the amount of organic waste sent to landfills, incinerators, or other disposal facilities, workers in waste management sector might face employment disruptions. Brand (2015) stated the broader consequences of job losses, which is significant in rural and remote areas, where such events can have far-reaching social and economic implications on affected workers and communities. With regard to the social attribute -the potential for public unrest surrounding organic fertilizer industrial process has various impacts on sustainability of its production. Sayara *et al.* (2020) stated that negative perceptions and attitudes from the public toward composting, fueled by concerns about issues such as odor, noise, pests, health risks, and aesthetics, trigger public unrest. This unrest, in turn, has the potential to undermine the social acceptance and active involvement of the public in composting initiatives. It could result in suboptimal waste separation, collection, and delivery practices, which significantly affect the overall effectiveness of composting initiatives. Purkiss *et al*. (2022) stated that public unrest also influences the policy and regulatory environment pertaining to composting. The pressure or resistance from the public shapes the development, implementation, and enforcement of composting initiatives, standards, incentives, and regulations. Finally, Purkiss *et al.* (2022) reported that public unrest hinders the market development and competitiveness of composting. The reduction in demand and supply of organic fertilizer products, driven by negative public sentiment, disrupts pricing strategies, distribution channels, and promotional activities in this industry. In relation to the impact of social attributes, specifically the Level of business motivation, this aspect has various effects on sustainability of organic fertilizer production. Mulasari *et al*. (2021) reported that entrepreneurship motivation drives investments and fosters innovation within waste management sector. This phenomenon triggers the development of enhanced technologies, greater efficiency, improved product quality, and heightened profitability. Soomro *et al.* (2023) stated that the level of motivation also influences the pursuit of guidance concerning issues related to market development and competitiveness of solid waste management. As a result, this affects factors such as the interplay between supply and demand, pricing strategies, distribution channels, and promotional efforts related to organic fertilizer products. Soomro *et al.* (2023) stated that business motivation shapes the policy and regulatory landscape surrounding organic fertilizer production. Businesses propelled by motivation often champion supportive measures because they adhere to industry standards and regulations and actively engage with relevant stakeholders to influence the overall policy environment. Furthermore, the insights provided by Zurbrugg and Ahmed (1999) reinforce this concept, suggesting that business motivation mirrors the social and environmental values intertwined with solid waste production. Zurbrugg and Ahmed (1999) also stated that business motivation reflects the social and environmental values associated with solid waste production. In essence, by aligning with principles like the circular economy, waste reduction, soil fertility, and climate change mitigation, motivated businesses contribute to the overarching sustainability goals of the composting industry. Considering the involvement of family members as a social attribute in green initiatives, it is evident that this factor has several impacts on sustainability of organic fertilizer production. Lunag *et al.* (2021) stated that family involvement contributes to increased awareness and participation of households in organic waste initiatives. This reduces the amount of waste sent to landfills and improves the quality of organic fertilizer feedstock (Idawati *et al*., 2023). Noufal *et al.* (2021) reported that family engagement in composting enhances the social and environmental values associated with this practice. By sharing their knowledge, experiences, and the benefits of composting, families foster a culture of waste reduction and soil fertility, spreading these ideals among their neighbors and communities. Brotosusilo *et al.* (2023) reported that family or community involvement goes beyond its societal implications to bolster the economic viability and resilience of solid waste management efforts. Families tend to use the resulting organic fertilizer on their farms or for gardening purposes, or they could decide to sell it to generate income. This diversified method reduces reliance on chemical fertilizer and external markets, enhancing economic independence. Moreover, Lunag *et al.* (2021) reported that family involvement in solid waste management promotes innovation and adaptation.These families often experiment with various composting methods, materials, and products that align with local needs, resources, and preferences, driving continuous improvement and customization, specifically within the composting process. The managers and entrepreneurs' education levels in organic fertilizer production industry significantly impact sustainability of the operations. It is important for university education to incorporate composting educational programs and training focused on maintaining soil fertility, preserving natural resources, and fostering more sustainable agricultural practices.

Economical dimension

The economic dimension gets the lowest sustainability index score (63,69%) but still meets sustainability criteria. Through leverage analysis, certain characteristics within this dimension are highly sensitive in influencing the financial viability of organic fertilizer production. These attributes encompass the betterment of Managers and workers welfare, optimal use of raw materials, potential for business scale expansion or success rate improvement, and the market absorption rate of the produced organic fertilizer, as shown in (Fig. 4). Improving the welfare of these employees involves various strategies, such as increasing salaries, providing better working conditions, fostering career advancement opportunities, and offering training programs. The effective use of raw materials in organic fertilizer offers multiple benefits, including cost reduction, increased productivity, reduced environmental impact, and overall sustainability. This efficient method reduces expenses related to procurement, transportation, processing, and organic fertilizer production waste costs. In terms of environmental considerations, the efficient use of raw materials emerges as a significant strategy to reduce adverse impacts. This includes reducing production waste, curbing energy consumption, and minimizing greenhouse gas emissions. Such a proactive method to raw material usage contributes significantly to the long-term sustainability of the company. Furthermore, enhancing the marketing of organic fertilizer products can substantially affect sustainability of its production in the studied areas. The presence of a viable market is integral to sustainability of any commodity-based business, as it facilitates the commercial exchange of products. Strengthened marketing endeavors yield considerable profits for farmers, empowering them to sustain and expand their agricultural operations. This perspective aligns with the previous study that underscores the pivotal role of marketing in driving the growth and sustainability of small, medium, and micro enterprises (SMMEs). For farmers to ensure sustainability, generating adequate income is crucial for reinvesting in their enterprises (Adesehinwa *et al*., 2019). This underscores the notion that organic fertilizer production is profitable and feasible for continued operations.

The contribution to the increase in the substitution of organic fertilizer refers to the degree to which the industry is able to replace the use of chemical types with organic products in agriculture or gardening practices (Tao *et al.,* 2015). According to Roy *et al*. (2021), achieving success in this regard requires greater emphasis on the development of organic fertilizer market, which contributes to the overall sustainability of the plants. It is evident that a significant contribution to the increase in the substitution of organic fertilizer plays a vital role in bolstering sustainability of the industry. Rashid and Shahzad (2021) stated that this method reduces the demand and consumption of fossil fuels and non-renewable resources used in production of chemical fertilizer. It also decreases greenhouse gas emissions and environmental pollution associated with chemical fertilizer while improving soil fertility. Limited contribution to the increase in substitution of organic fertilizer resulted in diminished sustainability. This scenario increases the demand for fossil fuels and non-renewable resources in chemical fertilizer production. It raises greenhouse gas emissions and environmental pollution while degrading soil fertility. Rashid and Shahzad (2021) stated that

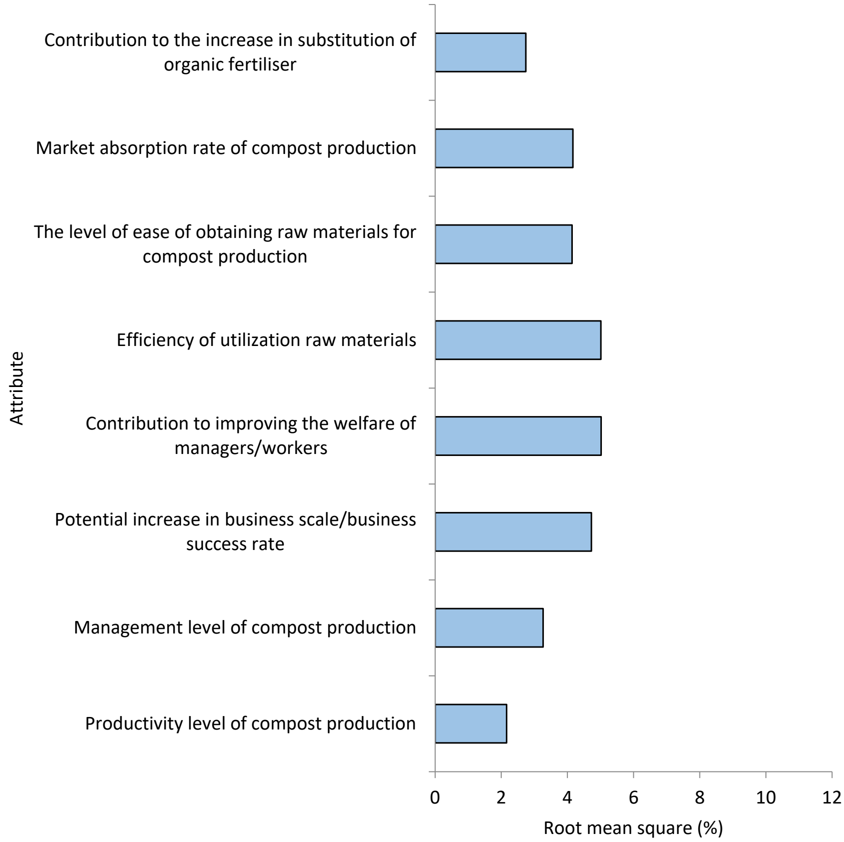

Fig. 4: Leverage of economical attributes

the contribution to the increase in the substitution of organic fertilizer also affects the economic and social sustainability of the industry. A substantial contribution tends to yield multiple benefits for the industry, including profitability and viability. This is achieved by fostering heightened demand and supply for organic fertilizer products. Such a situation influences crucial aspects like pricing, distribution strategies, and promotional efforts while generating income and creating employment opportunities. The market absorption rate of organic fertilizer production refers to the ratio of the quantity sold to the amount produced within a specific timeframe. This metric serves as an indicator of the ability to consume or absorb available organic fertilizer products. Pandyaswargo and Premakumara (2014) stated that a high market absorption rate indicates strong demand and a limited supply of these products. The earlier-mentioned scenario proves advantageous for organic fertilizer industry, enabling it to charge higher prices, increase profits, and expand production. Alexander (1990) reported that it also presents challenges such as maintaining quality standards, ensuring customer satisfaction, and competing with other sources of organic fertilizer. Conversely, a low market absorption rate suggests weak demand and an excess supply of these products. This scenario could be unfavorable for organic fertilizer industry, leading to lower prices, reduced profits, and surplus inventory. It also creates opportunities for enhancing product quality, promoting benefits, and diversifying the range of products and services the industry offers (Eggerth,1996). Focusing on municipal waste, McIllfaterick (2017) stated that the market absorption rate of organic fertilizer production also affects the environmental and social sustainability of the industry. The study further reported that a high market absorption rate reduces the volume of organic waste sent to landfills or incinerators while enhancing soil fertility. On the other hand, it leads to increased energy consumption and greenhouse gas emissions during organic fertilization and transportation processes. In order to achieve sustainability, organic fertilizer industry needs to strike a balance between economic, environmental, and social goals. Wilson (1989) stated that the feasibility of obtaining organic waste materials for organic fertilizer production relies on the availability, accessibility, and quality of its sources. These include agricultural and municipal solid wastes, as well as animal manure. Pergola *et al*. (2020) further reported that a high level of ease in obtaining raw materials for organic fertilizer production significantly facilitates the composting process. It ensures a consistent and sufficient supply of organic waste, reduces transportation costs and emissions while enhancing the quality and stability of the resulting product. A low level of ease in obtaining raw materials can impede the composting process, potentially leading to shortages or fluctuations in organic waste availability. This increases transportation costs and emissions and compromises the quality and stability of organic fertilizer product. Noor et al. (2023) propose that the ease of obtaining raw materials also has implications for the environmental and social sustainability of organic fertilizer industry. Noor *et al.* (2023) suggest that the level of ease in obtaining raw materials also affects the environmental and social sustainability of organic fertilizer industry. A high level of ease reduces the amount of organic waste sent to landfills or incinerators, benefiting soil fertility. The efficiency of raw material use in organic fertilizer production refers to the ratio of organic fertilizer products obtained to the quantity of waste used during the composting process. This metric highlights how effectively organic waste is transformed into fertilizer products. According to Pace *et al.* (1995), high efficiency of raw material use in organic fertilizer production enhances sustainability of the industry. It increases the yield and quality of the products, reduces waste generation and disposal, and improves overall resource efficiency and circularity. Ayilara *et al.* (2020) stated that enterprises and preliminary studies have considered using municipal garbage as raw materials. Low efficiency of raw material use in organic fertilizer production reduces sustainability. It reduces the yield and quality of organic fertilizer products, escalating waste generation and disposal and undermining overall resource efficiency and circularity. Singh (2021) reported that the efficiency of raw material use also affects the environmental and social sustainability of organic fertilizer industry. High efficiency reduces greenhouse gas emissions and energy consumption during composting and transportation processes while enhancing soil fertility. Ayilara *et al.* (2020) reported that this method might pose challenges, such as managing odor, pests, pathogens, and heavy metals in organic waste.

Technological dimension

The multidimensional analysis yielded a technological sustainability index 73.93% for organic fertilizer production using waste from rice straw and cow rumen contents. This value falls within the moderately favorable range, with a stress level of 0.148, categorizing it in the lowest stress group, as shown in (Table 4). From the results of this survey, it was inferred that the technology used in organic fertilizer production process is typically good. Despite its moderately favorable rating, there are still opportunities to enhance or adjust production technology, taking into account specific pros and cons within the manufacturing process. Leverage analysis highlights several factors influencing sustainability of organic fertilizer production technology. These include the level of managerial expertise required, the sensitivity of the method to the quality and quantity of organic fertilizer produced, the availability of facilities and infrastructure, as well as the potential for improving production technology or methods. The degree to which the local population embraces organic fertilizer production system is one of the most sensitive factors determining sustainability of the technological dimension, as shown in (Fig. 5).

The results of this study indicate that a certain level of expertise is optional for organic fertilizer industry managers. This suggests that production process is relatively straightforward to understand. The survey results show that organic fertilizer production, in terms of quality and quantity, is relatively sensitive to treatment variations during manufacturing. Indicators of the accessibility of facilities for producing organic fertilizer and the potential for technological advancements in production show reasonably acceptable values. However, there is still room for improvement. For small or medium-scale organic fertilizer production, fairly simple facilities and infrastructure are needed. This includes equipment such as choppers, grinders, and mixers, as well as storage spaces or buildings for housing organic fertilizer materials and facilitating the composting process. These essential facilities include investments with relatively low costs. The materials used for organic fertilizer production are primarily organic wastes such as rice straw, rumen contents, and cow manure. Supportive materials such as minerals, dolomite, molasses, and beneficial microbes are introduced to facilitate the process (Ginting, 2019). In the context of scaling up production, the incorporation of additional equipment becomes pivotal. This includes chopping and grinding equipment powered by electricity or fuel to make it more efficient. Simultaneously, establishing a permanent storage warehouse is imperative to ensure smooth operations. The indicators of the availability of manufacturing facilities and the potential for technological advancements are intertwined, playing a crucial role in their successful implementation. As technical progress is achieved, it necessitates parallel adaptations of manufacturing facilities and overall infrastructure to accommodate these innovations effectively. Improvements in organic fertilizer production technology and facilities are also related to sustainability in the economic dimension. The current study revealed modest organic fertilizer productivity based on production indicators. The infusion of technological improvements and upgrades in production facilities is anticipated to positively influence organic fertilizer output. Within the domain of environmental sustainability, a promising avenue emerges through the refinement of organic fertilizer production methods. One of production technologies or methods used to support sustainability in the environmental dimension is the development of superior microbial decomposition of organic matter, which speeds up the composting process. Moreover, reimagining the drying process for organic materials offers an opportunity to align with environmental objectives. Exploring innovations like dryers featuring solar cells and other environmentally friendly technologies holds promise. Apart from that, for drying organic materials, dryers with solar cells and other more environmentally friendly technologies could be developed, thereby supporting business sustainability from an environmental, economic, or social perspective. Another method that has the potential to be improved is optimizing the mixture of composted materials to ensure the resulting organic fertilizer is of good quality in terms of hygiene, stability, and maturity (Pezzolla *et al.*, 2021). Facilities and infrastructural development are levers to increase productivity and production. Aziz et al. (2018) highlight that economic analysis guides the management strategies within organic fertilizer production domain, aiming for efficiency while minimizing environmental burdens. Aziz *et al*. (2018) reported that management of organic fertilizer production area and the work methods

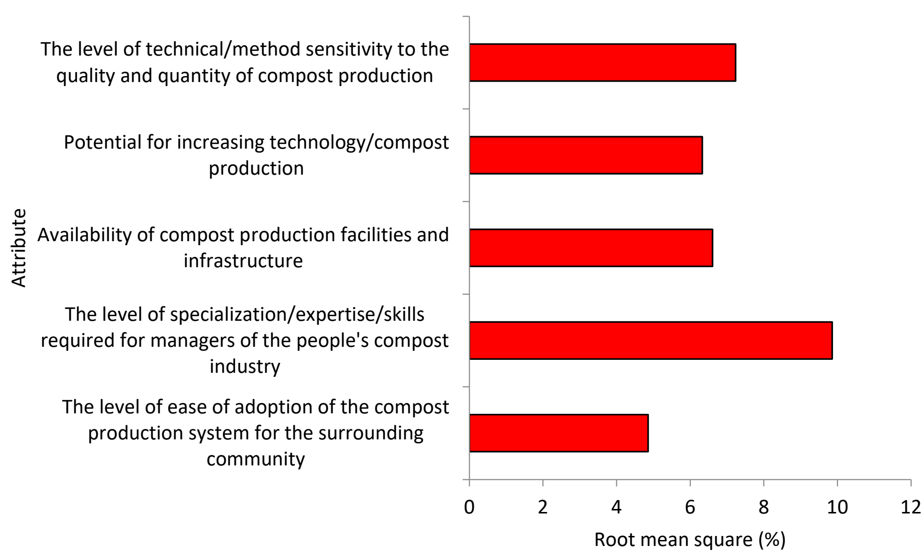

Fig. 5: Leverage of technology attributes

used are based on economic analysis to make it more efficient while minimizing environmental burden. This method encompasses critical aspects such as raw material storage and waste disposal. The simplicity of the composting method makes it accessible for implementation and adoption, even within the local community. However, the survey results indicate a heightened sensitivity to its adoption by the surrounding community, particularly concerning technological sustainability. This is presumably due to a knowledge gap within the local community pertaining to the significance of organic fertilizer in enhancing plant growth, augmenting soil fertility, and contributing to environmental preservation. The community appears to lack awareness of the promising economic value intertwined with organic fertilizer production. As a result, it becomes imperative to initiate focused efforts to enhance the acceptance indicators of organic fertilizer production system, thereby boosting the overall sustainability of the technical dimension. To address this challenge, targeted initiatives must be deployed to capture and sustain the interest of the community in organic fertilizer production derived from rice straw waste and cow rumen contents. This involves comprehensive socialization of production system, technology-centric exhibitions, practical emulation studies, and specialized training facilitated through collaborations with technology and business institutions. Therefore, the five technological dimension attributes studied still have the opportunity to be improved or developed by considering related aspects such as environment, economy, and society. Pergola *et al*. (2020) reported that the adoption of organic fertilizer production methods by farmers requires an evaluation of the environmental impact, energy consumption, and economic costs, specifically regarding the construction and management of facilities. Finally, production procedures rely on government support and careful consideration of key technological factors to achieve optimal and sustainable production. The Indonesian government is recommended to undertake the following roles. Regulations and Incentives: The government could enact policies encouraging proper waste management, potentially offering incentives to promote sustainable practices such as composting and waste conversion. Research and development Support: Investment in research is vital to optimize waste-to-fertilizer conversion. Government funding could substantially contribute to the development of efficient processing methods. Financial Boost: Provide financial support, subsidies, or grants to encourage organic fertilizer production among farmers, cooperatives, and businesses. Capacity Building: Government-led training sessions to educate stakeholders on organic fertilizer benefits, composting, and waste management best practices. Collaboration: Public-private partnerships involving the private sector, non-goverment organisations (NGOs), and international bodies can amplify expertise, resources, and scaling potentials. Market Creation: Government efforts to connect organic fertilizer producers to potential buyers in order to stimulate investment.

CONCLUSIONS

In conclusion, sustainability index for organic fertilizer production was determined using MDS method, considering factors affecting sustainability across four dimensions. The calculated sustainability index was 74.55%, indicating the growth potential when considering leverage factors in each dimension. The developed sustainability index was valid and limited in the area where it was developed due to diverse regional characteristics. Among these, the economic dimension had the lowest leverage value at 63.69%, while that of environmental, social, and technological were obtained at 90.1%, 70.5%, and 73.93%, respectively. Improving the economic aspects was prioritized, particularly those related to production and marketing. In terms of the environmental dimension, enhancing water efficiency during fertilizer production emerged as a pivotal factor. Efficient water use, specifically in high-water-usage environments such as paddy fields, reduces water waste, preserves resources, and supports environmental sustainability. The benefits of organic fertilizer were also recognized for countering soil degradation and enhancing its quality, as well as conserving groundwater. In the social dimension, addressing factors such as job security, community engagement, and knowledge levels of workers and managers was identified as crucial for achieving sustainable implementation. Strategies such as retraining, stakeholder engagement, communication, and capacity-building were deemed essential for promoting community well-being and fostering a sustainable agricultural system. Various factors, including worker welfare, raw material use, market expansion, and substitution of chemical fertilizer, influenced the economic dimension. The significance of strong marketing efforts in increasing profits and adoption rates was underscored. In the technological dimension, factors such as managerial expertise, production methods, availability of production facilities, and community adoption ease were recognized as influential in achieving sustainable organic fertilizer production. Finally, it was emphasized that government support and technological considerations were vital for promoting sustainable organic fertilizer production in Indonesia, specifically given the escalating demand for national fertilizer.

AUTHOR CONTRIBUTIONS

A.D. Santoso conducted the literature analysis, experimental activities, writing of the manuscript, getting result, data handling, data validation, MDS data analysis, analyzed the manuscript critically for significant intellectual content; F.D Arianti conducted the literature analysis, experimental activities, writing of the manuscript, data handling, MDS data analysis, analyzed the manuscript critically for significant intellectual content; E.S. Rohaeni conducted the literature analysis, writing of the manuscript, data and information collection, data handling, MDS data analysis, analyzed the manuscript critically for significant intellectual content; B. Haryanto conducted the literature analysis, experimental activities, writing of the manuscript, MDS data analysis, analyzed the manuscript critically for significant intellectual content, administration; Pertiwi, M.D conducted the literature analysis, experimental activities, writing of the manuscript, administration; L.P. Panggabean conducted the literature analysis, writing of the manuscript, data and information collection, data handling, analyzed the manuscript critically for significant intellectual content; A. Prabowo conducted the literature analysis, experimental activities, writing of the manuscript, data and information collection, MDS data analysis; S. Sundari conducted the literature analysis, writing of the manuscript, data and information collection, analyzed the manuscript critically for significant intellectual content; S.P. Wijayanti conducted the literature analysis, writing of the manuscript, experimental activities, data and information collection, MDS data analysis analyzed the manuscript critically for significant intellectual content; I.N. Djarot conducted the literature analysis, experimental activities, writing of the manuscript, MDS data analysis, analyzed the manuscript critically for significant intellectual content; F.D. Kurniawati conducted the literature analysis, writing of the manuscript, analyzed the manuscript critically for significant intellectual content; F.L. Sahwan conducted the literature analysis, experimental activities, writing of the manuscript, validation, MDS data analysis, analyzed the manuscript critically for significant intellectual content; T. Prasetyo conducted the literature analysis, experimental activities, writing of the manuscript, validation, MDS data analysist; A. Barkah conducted the literature analysis, writing of the manuscript, experimental activities, data and information collection, administration; T.A. Adibroto conducted the literature analysis, experimental activities, writing of the manuscript, validation, MDS data analysis, analyzed the manuscript critically for significant intellectual content; R. Ridlo conducted the literature analysis, experimental activities, writing of the manuscript, analyzed the manuscript critically for significant intellectual content; I. Febijanto conducted the literature analysis, experimental activities, writing of the manuscript, data and information collection, analyzed the manuscript critically for significant intellectual content; A.A. Wasil conducted the literature analysis, writing of the manuscript, data and information collection, data handling, administration; S. Lusiana conducted the literature analysis, writing of the manuscript, validation, MDS data analysis, administration; R. Rosmeika conducted the literature analysis, writing of the manuscript, validation, MDS data analysis, administration; Heryanto, R.B. conducted the literature analysis, experimental activities, writing of the manuscript, analyzed the manuscript critically for significant intellectual content.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication, double publication and submission, as well as redundancy, have been completely witnessed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
°C	Degree Celsius
ADF	Acid detergent fiber
ADL	Acid detergent lignin
ASCAL	Alternating least-squares algorithm
APHA	American public health association
C	Carbon
Ca	Calcium
CH_4	Methane
C/N ratio	Carbon-nitrogen ratio
CF	Crude fiber
CP	Crude protein
CSR	Corporate social responsibility
d	Euclidian distance
d_{ij}	Euclidian distance from point i to point j
d_{ijk}	Squared distance
FAO	Food and agriculture organization
DM	Dry matter
GDP	Gross domestic product
GKG	Dry milled grain
GWP	Global warming potential
H	Hydrogen
K	Kalium
kg	Kilogram
LCA	Life cycle assessment
Ltd	Limited
MC	Moisture content
MDS	Multidimensional scaling
mg	Milligram
$mgCH_4/kg$	Miligram methane per kilogram substrate
N	Nitrogen
Na	Natrium
NA	Not applicable
NGOs	Nongovernment organizations
O	Oxygen
P	Phosphorus
pH	Potential of hydrogen
ppm	Part per million
Raffish	Rapid appraisal for fisheries, an analytical method to assess sustainability of fisheries based on a multidisciplinary method
RH	Relative humidity
RMS	Root mean square, a frequently used measure of the differences between values
S	Sulphur
SR^2	Squared correlation
SQR	Structured query reporter, a programming language designed for generating reports from database management systems
TKN	Total Kjeldahl Nitrogen
TS	Total solid

USD	United States dollar
VS	Volatile solid
x-axis	Horizontal number line
y-axis	Vertical number line

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SPECIAL ISSUE: Eco-friendly sustainable management
ORIGINAL RESEARCH PAPER

Barriers to sustainable green innovation in meeting the challenges of the global economy of firms

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ABSTRACT

BACKGROUND AND OBJECTIVES: Sustainable innovation is crucial, because it is a key strategy for ensuring the long-term survival of companies in a world with limited resources. Consequently, understanding the barriers faced by companies in achieving sustainable innovation, such as high initial cost, lack of technical knowledge, or unclear regulations, is important for developing appropriate policies, strategies, and solutions that promote and facilitate its adoption.
METHODS: This study aims to analyze the relevant and most important scientific evidence and research topics on barriers to sustainable innovation through a bibliometric analysis combined with concurrence networks and cluster analysis using VOSViewer.
FINDINGS: Research on barriers to innovation was developed on a larger scale in 2012 with an average growth of approximately 43 percent until 2022. During this period, the study on green innovation has been predominant and on the social component of sustainable innovation to a lesser extent. Asia, specifically China, is leading the research on this topic mainly on the environmental component of sustainable innovation. In terms of barriers, the majority of the literature focus on financial constraints. The research agenda focus on the following areas or clusters: sustainability, barriers to sustainable innovation, and social innovation.
CONCLUSION: The major barriers to sustainable innovation are financial and government regulations. The current research tackles the environmental component of sustainable innovation. Therefore, future research should focus on market and knowledge barriers in developed and less developing countries and on the social component of sustainable innovation. Potential areas of research (which are underexplored) exiest and can be important for future research on enhancing knowledge about barriers to sustainable innovation: applied research that considers regional effects and country-specific analysis, in particular in developing countries. Research on the social component of sustainable innovation could be relevant. Social innovation is essential, because it addresses concrete societal problems and promotes collective action and inclusion in novel ways within companies.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF eS
54	8	2

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INTRODUCTION

Sustainable innovation is a complex concept that is frequently associated with other terms such as environmental innovation, eco-innovation, green innovation, or ecological innovation (Degler *et al.,* 2021). However, elucidating that sustainable innovation is a broader aspect that encompasses the aforementioned terms and includes social components, which is known as social innovation, is essential (Schiederig *et al.*, 2011). In other words, sustainable innovation consists of environmental and social components. In addition, sustainable innovation is defined as the introduction of novel, changed, or improved products, services, or processes within an organization that intends to generate long-term social and environmental benefits while considering commercial or economic gains (Shields, 2022; Degler *et al.,* 2021; Fields and Huesig, 2019). The significant growth of the global economy has led to alarming environmental problems such as climate change and increased scarcity in energy and resource (Degler *et al.*, 2021; Puno *et al.,* 2021; Rodelo-Torrente *et al.,* 2022). To understand the contribution of innovation to sustainability and to mitigate these issues, internalizing and apply concepts inherent to business management are essential aspects (Tidd and Bessant, 2020). Organizations are currently engaging in innovation ecosystems to fulfill the Sustainable Development Goals established by the United Nations (Nylund *et al.*, 2021), typically with the help of new approaches such as frugal innovation (Ebolor *et al.*, 2022). Nowadays, organizations must be sustainable by conducting their activities following economic, social, and environmental principles. The sustainable development of organizations relates to all forms of innovation, particularly those related to changes in organizational methods and management (Koziol and Beyer, 2021). With the increasing interest of stakeholders in sustainability-related issues (Awan and Sroufe, 2020), research focuses on the distinction between traditional and sustainable innovation with the objective of understanding their determinants (Moghadam and Samimi, 2022). However, the literature primarily highlights the determinants that drive sustainable innovation while it needs to pay more attention to research on the determinants that hinder or impede this type of innovation (Pinget *et al.*, 2015; Nouri, 2022). With respect to firm size, the literature gap is increasingly pronounced on small- and medium-sized enterprises (SMEs) despite these types of companies representing approximately 90 percent (%) of total businesses worldwide (World Bank, 2019) and accounting for more than 60% of industrial pollution (Kumar *et al.*, 2022). In this regard, SMEs play a crucial role in global sustainable development issues and are an important target for public policies to foster a sustainable society. However, SMEs face unique challenges, because as they are frequently constrained by relatively limited resources despite their desire to reduce environmental impacts (Pinget *et al.*, 2015). This study aims to analyze research topics on barriers to innovation from the social and environmental perspectives to elucidate the most recent scientific developments and research gaps on this topic. The remainder of this document is organized as follows: the following section presents the methodology followed by the research findings and discussion. The final section highlights the main conclusions and limitations of the study. It also outlines future research directions that emphasize the social component of sustainable innovation, the role of knowledge and market barriers, and the analysis of this thematic area in developing countries. Furthermore, the study aims to analyze research topics on barriers to sustainable innovation in an effort to understand the most recent scientific developments and research gaps on this topic. In this sense, this study aims to answer the following research questions: What are the most relevant topics in the scientific literature on sustainable innovation? Do research gaps on sustainable innovation exist? What could be future research agenda? This study was conducted in Colombia in 2023.

MATERIALS AND METHODS

This study has been conducted through data identification, filtering, and systematization, to analyze research topics on barriers to sustainable innovation. Bibliometric and descriptive analyses were performed using the document analysis approach (Liniers and Cruz, 2020). Information search was conducted using the well-known citation database SCOPUS, which contains the most relevant scientific literature worldwide (Abdullah, 2021; Bass *et al.*, 2020). This study followed the work of scholars such as Abdullah (2021), which have conducted bibliometric studies. The bibliometric analysis was conducted following the selection strategy and research protocol adapted from the PRISMA flowchart (Moher *et al.*, 2009). The adopted inclusion criteria are as follows, journal articles published in scientific journals, a time range from 1975 to 2023, and documents published in English and Spanish. The search strategy included the following descriptors: ("Eco? innovation" OR "Sustainable Innovation" OR "Innovación Sostenible" OR "green innovation" OR "Innovación verde" OR "environmental Innovation" OR "Innovación Ambiental" OR "Ecological Innovation" OR "Innovación Ecológica" OR "Social Innovation" OR "Innovación Social") AND (barrier* OR Barrer* OR Obstacle* OR Obstacu* OR Constraint* OR Restricc* OR hinder* OR Difficult*)

For a better understanding of the strategy for document search, Table 1 provides a description of the different logical operators used in SCOPUS.

After applying the search equation, the study obtained a total of 850 documents, specifically 628 journal articles, 98 conference papers, 58 book chapters, 35 reviews, 15 books, 8 letters to the editor, 5 conference reviews, and 3 notes. The research objective was to analyze topics in barriers to sustainable innovation; thus, only journal articles were selected for content analysis to identify the most scientifically impactful documents. In this regard, the following type of documents were excluded: conference papers given that access to an entire document is impossible (Scherer and Saldanha, 2019), books and book chapters, because not all books are academic or follow a well-defined methodological framework (Edinger and Cohen, 2013), reviews, editorials, notes, short surveys, and data documents that are not considered original research. Following the inclusion criteria, a sample of 628 articles was obtained. In addition, 27 documents were excluded for being written in languages apart from English or Spanish, which resulted in a final sample of 598 documents. Notably, in literature reviews, a few authors only use the language in which they are familiar to facilitate content analysis (Bahji *et al.*, 2022). Fig. 1 illustrates the document selection strategy and research protocol. The metadata of the final sample (598 documents) were exported in CSV format to Microsoft Excel and VOSviewer for analysis. The metadata included the information, document source, publication year, publication title, country, journal title, thematic area, abstract, and publication type of the authors. Using VOSviewer, which was developed by Van Eck and Waltman (2019), the study conducted analysis and mapping of publications on barriers to sustainable innovation. According to Van Eck and Waltman (2019), VOSviewer uses visual elements based on mapping techniques to transform CSV data into diagrams or clusters. The mapping techniques allow the researcher to analyze relevant information such as authors, co-occurrences, organizations, citations, and co-citations (Khalil and Crawford, 2015). To identify topics based on keyword co-occurrences, the core terms of the search equation (i.e., sustainable, environmental, eco-, ecological, and social innovation) were excluded. These terms represent the central terms of the search equation, and the objective is to discover other parallel research topics related to sustainable innovation. If these terms were included in the VOSviewer visualization, then they would form the

Table 1: Database logical operators in SCOPUS

Logical operator	Description
AND	Words separated by spaces will be processed with the AND operator. It retrieves documents that contain both words.
OR	Retrieves documents that contain at least one of the words.
""	By placing words in quotation marks, approximate results are sought. It searches for singular and plural forms (with exceptions).
*	The asterisk replaces any number of characters at the end of a word. Example: Innova* searches for innovation, innovative, etc.
( )	This operator allows charging the order of priority of different logical operators.
TITLE-ABS-KEY	Indicates that it will only search for documents containing the required information in the title, abstract, and keywords.

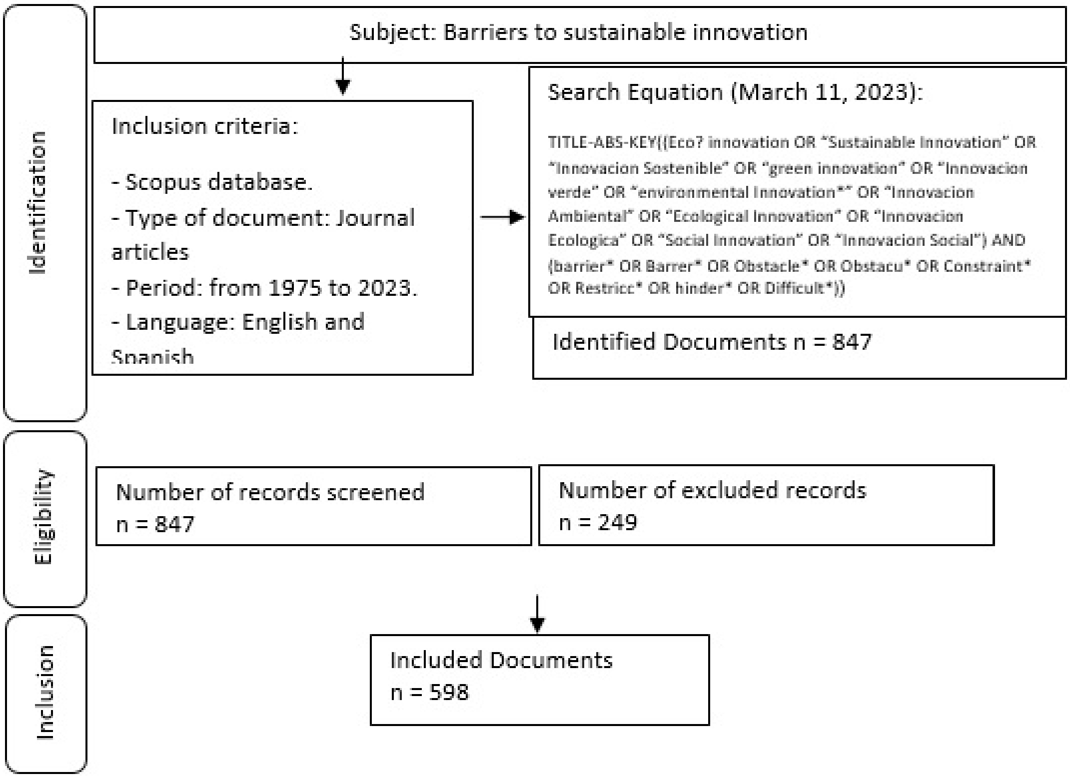

Fig. 1: Document selection strategy and research protocol

central clusters of the visualizations, because they are the keywords used in the search equation and would, therefore, appear most frequently. The number of co-occurrences applied to cluster and network visualization was seven compared with the default five co-occurrences set by the software. Co-occurrence intends to identify topics with greater significance. Additionally, two coauthorship visualizations were conducted to identify research networks and clusters.

RESULTS AND DISCUSSION

Eisenberg (1975) conducted the first publication on the topic in the field of medicine (Fig. 2) and found that social innovation in childcare is necessary for providing optimal conditions for child development during a period of transitioning family roles. The author highlighted that parents face psychological barriers to child care. Afterward, a 13-year period without publications occurred until Milton and Demment (1988) also published in medicine and social innovation followed by intermittent periods of publication such as Stangvik (1989) and Wong *et al.* (1996). From the year 2000 onward, research publication increased with an average of 1.6 publications per year between 2000 and 2007. During this period, articles by Biondi *et al.* (2002) and Le *et al.* (2006) stand out with 116 and 103 citations and represent the two most cited documents during this period. Both articles emphasize the importance of environmental innovation in SMEs and the hospitality and hotel businesses. The most cited studies referred to environmental innovation; however, a few studies used the term sustainable innovation.

A significant increase in the number of publications began in 2012 with an average growth rate of 43% until 2022. During this period, Rizos *et al.* (2016) was the most relevant publication in terms of citations (435 citations) and focused on the barriers and facilitators faced by SMEs in implementing a circular economy as a green innovation strategy. The results

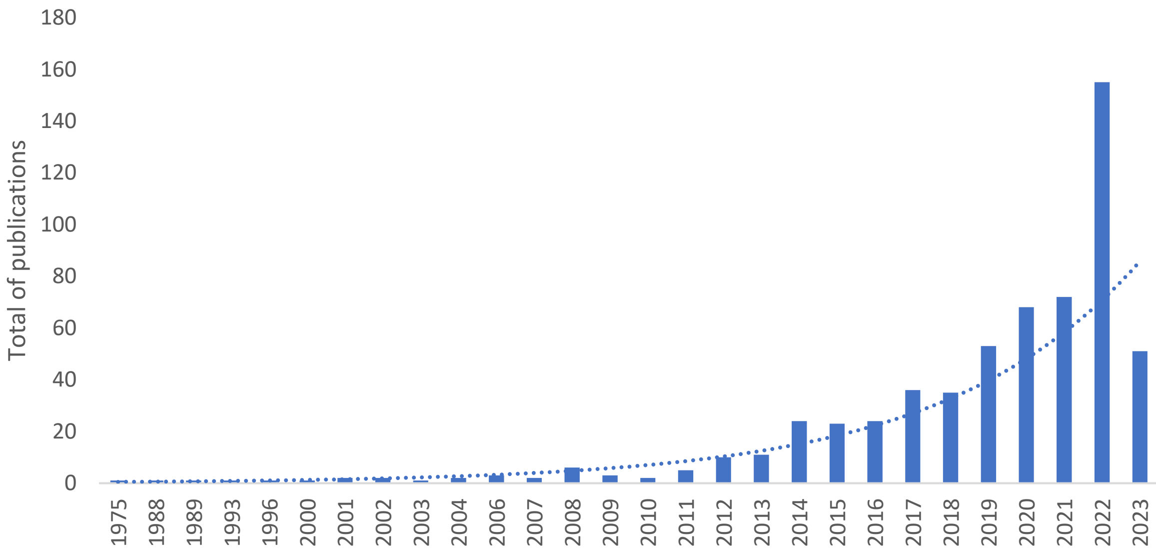

Fig. 2: Number of journal articles published (1975–2023)

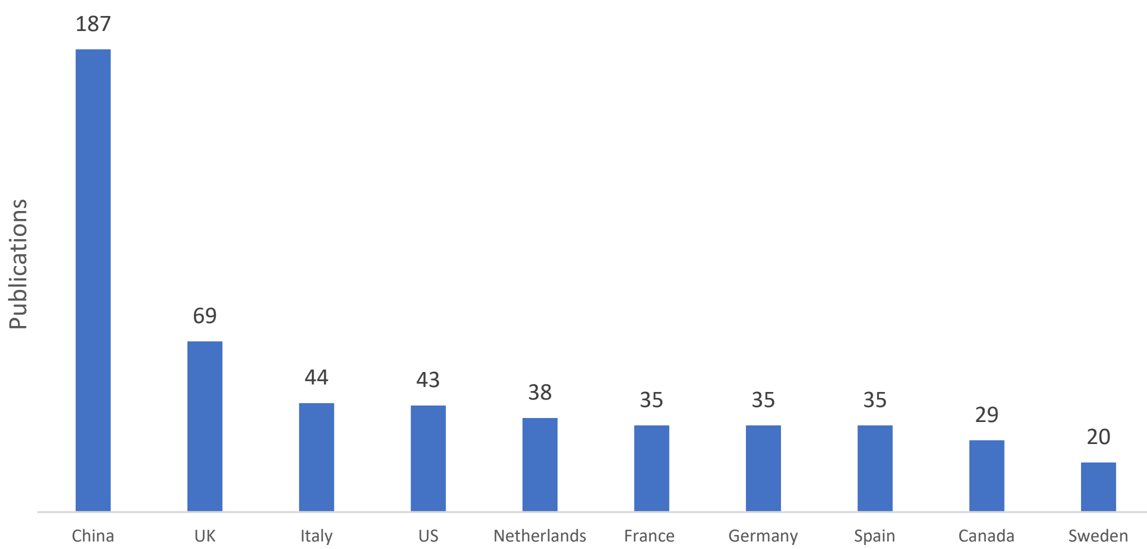

Fig. 3: Number of publications by selected countries (top 10; 1975–2023)

demonstrated that the lack of demand, capital, and government support are the main barriers for firms. Other influential studies (based on citations) focused on the determinants of green innovation in low-tech SMEs; green/environmental innovation and service capabilities; relationship among green innovation, external sources of knowledge, and organizational performance; and social and environmental innovation. In this sense, the most relevant studies in this period addressed the topic of green innovation. As of March 2023, 50 articles were published, and the most cited ones include that of Ramzan *et al.* (2023), who identified the contribution of green innovation to sustainability and energy transition, and of Liang and Xu, (2023), who analyzed the efficiency of the implementation of sustainable innovation in China.

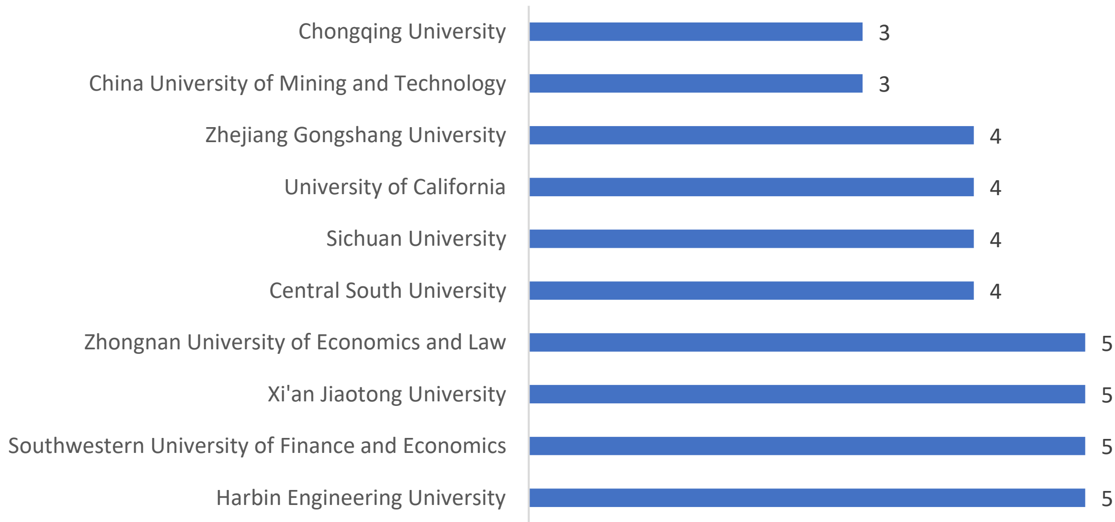

Fig. 4: Number of publications by institution (top 10; 1975–2023)

Table 2: Number of publications by journal title

Journal title	Number of research articles	Journal H-index	Journal SJR quartile
Sustainability (Switzerland)	61	136	Q1
Journal of Cleaner Production	40	268	Q1
International Journal of Environmental Research and Public Health	18	167	Q2
Environmental Science and Pollution Research	15	154	Q1
Frontiers in Environmental Science	11	61	Q1
Energy Economics	10	187	Q1
Technological Forecasting and Social Change	9	155	Q1
Business Strategy and the Environment	8	131	Q1
Ecological Economics	8	236	Q1
Resources, Conservation, and Recycling	6	170	Q1

Fig. 3 depicts the top 10 countries with the most number of publication on the barriers to sustainable innovation. China leads with 187 publications followed by the United Kingdom (69), Italy (44), the United States (43), the Netherlands (38), France (35), Germany (35), Spain (35), Canada (29), and Sweden (20). Unsurprisingly, China has the highest number of publications given that it is one of the largest CO_2 emitters worldwide (Shpak *et al.*, 2022). When analyzing the top five articles published in China with the highest impact in terms of citations, all of them refer to the environmental component of sustainable innovation and explicitly use the term green innovation. These articles addressed the following research questions: Can green innovation mitigate financial barriers? What are the regional differences in green innovation efficiency? What is the role of green innovation in mitigating barriers to accessing green credits and government incentives? What is the effect of green innovation on industrial agglomeration? What is the mediating effect of financial barriers on environmental, social, and governance rating events with corporate green innovation?

Consequently, the universities with the highest number of publications are from China. Nine out of ten universities (Fig. 4) that published the most (90%) are Chinese, which focus on green innovation. The University of California can be found in the list (top 10) of universities with a higher number of

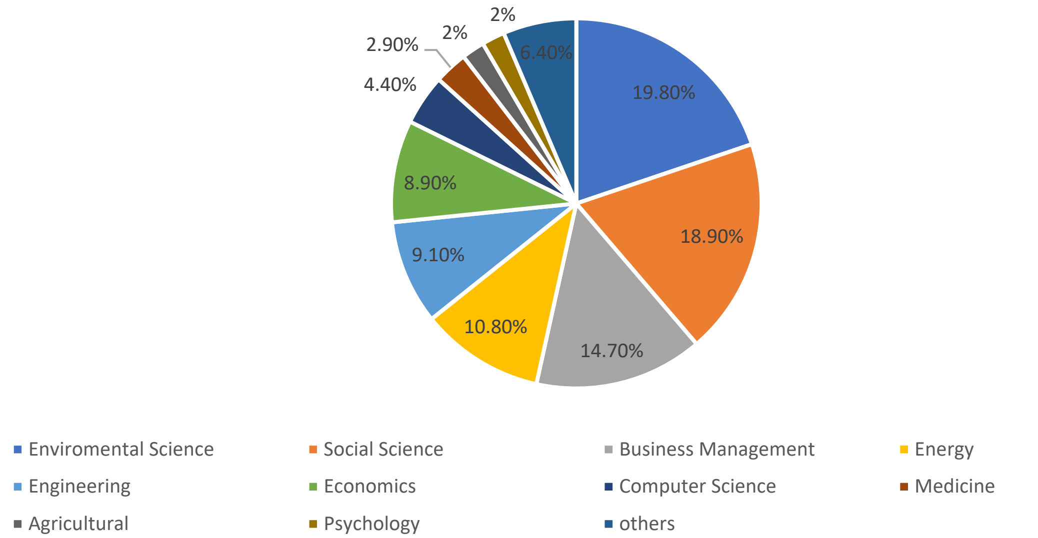

Fig. 5: Publication by thematic areas (%)

publications, and one of its research articles focus on the Chinese industry.

With respect to scientific journals, Table 2 present the most prestigious journals that published the most number of articles. Specifically, *Sustainability* published relevant and influential research articles such as Rizos *et al.* (2016) with 435 citations and Feng and Chen (2018) with 163 citations. Notably, the majority of the publications in these journals focus on the environmental components of sustainable innovation: green innovation and eco-innovation. However, a few articles address the social component of innovation from the perspective of government barriers. The most cited works in the *Journal of Cleaner Production* are Cuerva *et al.* (2014) and Foxon and Pearson (2008) with more than 100 citations. These articles analyzed the barriers to sustainable innovation in low-tech SMEs and companies with circular economy processes. With respect to journal quality, nine journals in the top-10 list exhibited the highest scientific impact (quartile 1) based on the Scimago Journal Report. The *International Journal of Environmental Research and Public Health* is in the second quartile (Q2), and its most cited articles are on green innovation in China. Alternatively, considering the Hirsch Index (or H-index) of scientific impact, the *Journal of Cleaner Production* and *Ecological Economics* stand out with H-indexes of 268 and 236, respectively.

The thematic areas or disciplines (Fig. 5) that published on the barriers to sustainable innovation are Environmental Sciences (19.8%), Social Sciences (18.9%), Business Management (14.7%), Energy (10.8%), and Engineering (9.1%).

To enrich the analysis, a visual keyword co-occurrence evaluation of documents (Fig. 6) was conducted. The figure depicts a keyword network diagram in which color, node, font size, and line thickness illustrate the relationship with other keywords (Sweileh *et al.*, 2017). A total of 16 keywords are identified and grouped into four nodes (i.e., presented in green, red, yellow, and blue). The keyword "sustainability" in the red nodes is the most relevant, which is indicated by node size and font (Sweileh *et al.*, 2017). In addition, the networks of authors are important for identifying the most relevant contributions, clusters, and co-authorships on barriers to sustainable innovation. Fig. 7 presents the minimum number of articles per author (set as one) to determine all potential links between authors. Chinese researchers lead the research networks that published the most on barriers to sustainable innovation. This finding corroborates that the majority of academic literature on this

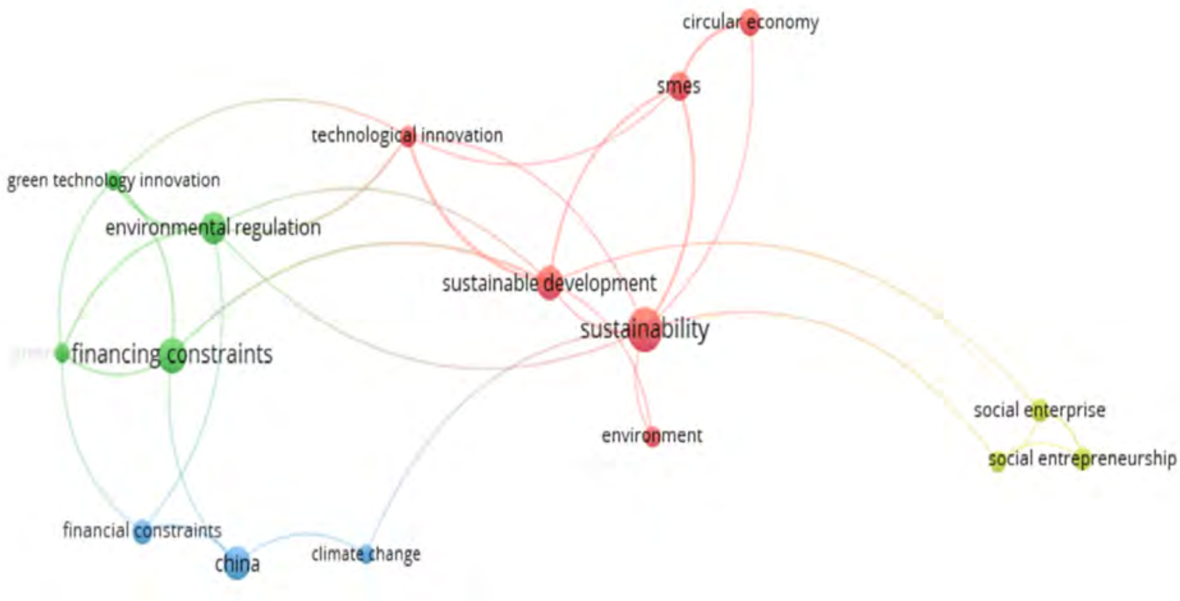

Fig. 6: Visualization of keyword co-occurrence

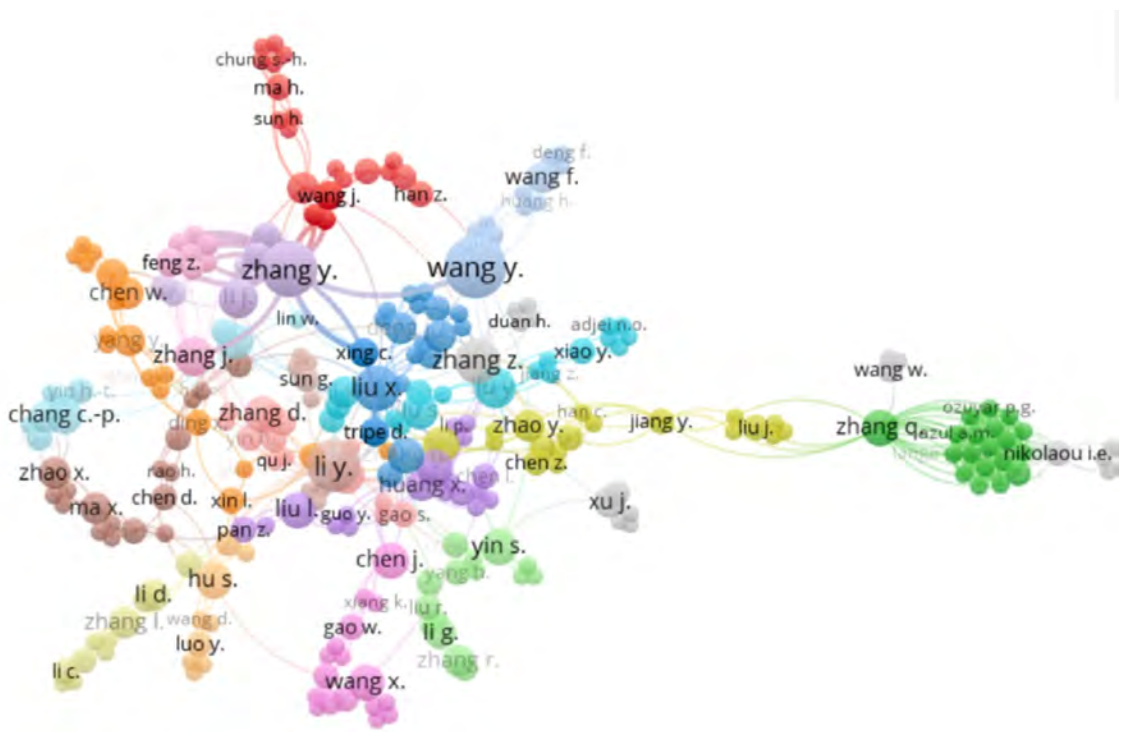

Fig. 7: Visualization of co-authorship (one document)

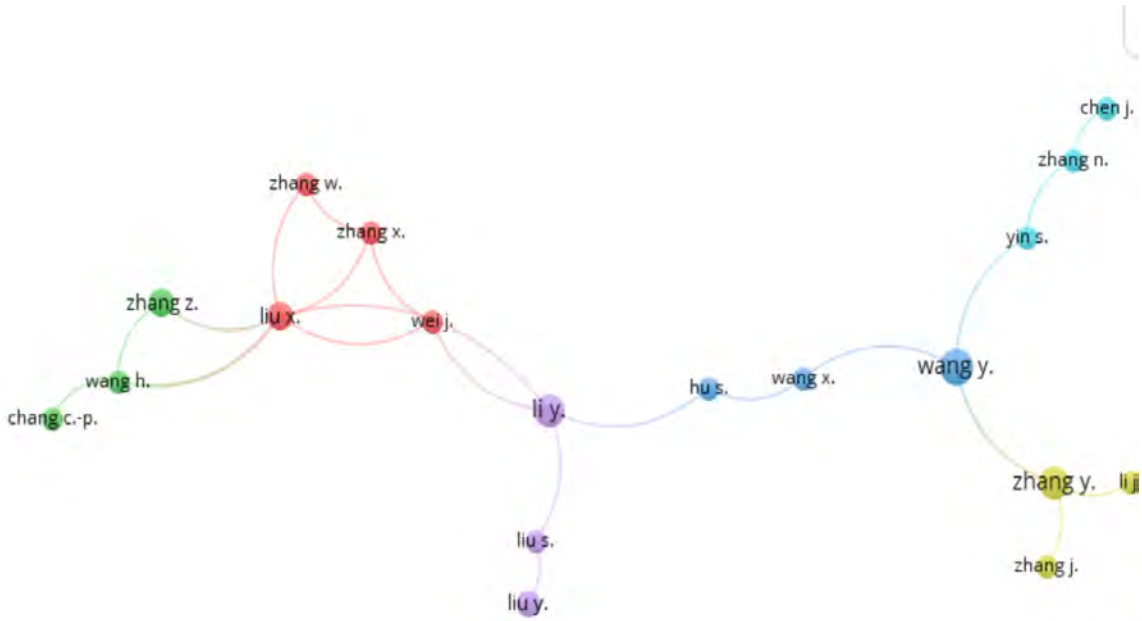

Fig. 8: Visualization of coauthorship (four documents)

topic is conducted by Chinese institutions and illustrates their commitment to sustainable development and to address these phenomena. To identify consolidated clusters related to barriers to sustainable innovation, the minimum number of documents per author in the co-authorship network was increased to four using VOSViewer (Fig. 8). It shows six main co-authorship clusters with a number of interconnections. The blue cluster (Hu, S.; Wang, X. and Wang Y.) is the central cluster, because it connects with three of the five remaining clusters. An important researcher is Wang Y., who addresses financial, regulatory, and market barriers in the manufacturing and logistics sectors. Another notable researcher is Li Y., who focuses on efficiency and green innovation in China. Nevertheless, Chinese researchers lead all clusters and collaborate within institutions.

The central aspect of the results is that the majority of the academic literature on barriers to innovation is concentrated in China based on the number of published research articles (Fig. 3), the largest number of institutions publishing on the subject (Fig. 4), and the most extensive participation in coauthorship networks (Figs. 7 and 8). Their work focuses on the emergence of green finance as an alternative solution to financial barriers to green innovation, on regulatory barriers on green innovation and sustainable industrial development, and the stimulation of green innovation using green credit policies, which, consequently, decreases the pollution of Chinese companies. Apart from research that is developing mainly in China, it primarily focuses on the environmental component of sustainable innovation, which leaves the social component in the background. However, citing that non-Chinese authors have developed relevant research on the social component of innovation is essential; notably, Westley *et al.* (2015) analyzed the barriers to social innovation among non-profit organizations in Canada. Here, we can also mention the works of Avila and Campos (2018) in Europe and Chalmers (2013) in the United Kingdom, among others. Another notable aspect that research conducted by western scholars, such as Rizos *et al.* (2016), focuses on SME companies in the European Union. They argue that a number of barriers still need to be addressed despite public policies for companies to innovate and join the circular economy. Other relevant research includes Cuerva *et al.* (2014) in Spain, Foxon and Pearson (2008) in the United Kingdom, and Fernando *et al.*

(2019) in Malaysia, whose research focused on how clean technologies mitigate the barriers to green innovation as well as generate economic growth. Despite the majority of authors and research being related to China, the top 10 journals that published on barriers to innovation are European journals (and only one from the United States). The journal *Sustainability* from Switzerland stands out with research on sustainable innovation. For instance, Feng and Chen (2018) found that green product innovation plays a particular promotional role in the absence of environmental regulatory barriers, while green craftsmanship innovation exerts a significant inhibitory effect. However, in the presence of environmental regulatory barriers and market-based environmental regulations, promoting green craftsmanship innovation instead of green product innovation positively impacts the ecological development of the industry. Through cluster analysis (Fig. 6), a number of hot topics on barriers to sustainable innovation emerge. Cluster 1 (red) depicts sustainability as an important area of research, as organizations frequently pursue sustainable innovation to improve their social and environmental impacts and achieve sustainable development (Cirone *et al.*, 2023; Feng *et al.*, 2022). Within this topic, many authors examined the contribution of these types of innovation to the development of circular economy systems (Herrero *et al.*, 2022; Austin and Rahman, 2022). Cluster 2 (green) indicates research that focuses on financial and regulatory barriers to sustainable innovation, such as financial barriers (Zhai *et al.*, 2022; Zhao *et al.*, 2023) and barriers related to government regulations (Zhang *et al.*, 2023). Cluster 3 (blue) refers to climate change issues. The majority of research in Clusters 2 and 3 focus on China. Finally, Cluster 4 (yellow) depicts the lowest number of nodes and refers to the social component of sustainable research, in which social entrepreneurship (Jarrar, 2022; Yeasmin and Koivisto, 2017) and social enterprise (Zainol *et al.*, 2019; Kim and Lim, 2017) stand outs. The nodes in this cluster are related to sustainability and sustainable development, thus, identifying research such as that conducted by Zainol *et al.* (2019), who found that social innovation helps to identify social problems and guide actions for addressing complex social issues through the capabilities of social enterprises. Additionally, the authors argue the potential of the capabilities of social enterprises to expand social innovation in the economy.

CONCLUSION

The current study aimed to elucidate the barriers faced by companies in achieving sustainable innovation. The bibliometric analysis led to certain significant conclusions which are described as follows.

First, notably, the literature on barriers to sustainable innovation has been growing since the 2000s; however, it began to develop on a larger scale in 2012 with an average growth of approximately 43% until 2022. During this period, research on green innovation has become predominant and on the social component of sustainable innovation to a lesser extent. In the first quarter of 2023, a total of 50 research articles were published; if this trend persists, then scholars expect that approximately 200 articles will be published by the end of 2023. The latter exhibits an increasing interest in green innovation and the barriers that may constrain this development. Asia is leading the research on this topic. For instance, China takes the lead with the most number of research on barriers to sustainable innovation, as one of the most polluted countries in the world. Research in China also focuses on the environmental component of sustainable innovation; in terms of barriers, the majority of the literature highlight financial constraints. The predominance of China as the country with the largest number of research published illustrates the relative importance of Chinese institutions and researchers toward working on barriers to innovation. Nevertheless, European academic journals are those that published the most in these topics, specifically on the environmental component of innovation. Analysis of the clusters points to the major topics related to sustainable innovation. One of the key areas of research focuses on sustainability, especially on its environmental component, and the barriers faced by firms to achieve sustainable development under climate change conditions. Alternatively, research focuses on the barriers to innovation, which illustrates that it emphasizes financial and regulatory barriers. Finally, the social component of sustainable development remains underexplored, specifically on entrepreneurship and social enterprises. Accordingly, future research agenda should consider potential areas of work to enhance knowledge about barriers to sustainable innovation, that is, applied research that considers regional effects and country-specific analysis, particularly in developing countries. Research on the social component of sustainable innovation could be relevant given the current bias toward the environmental components. Social innovation is essential, because it addresses concrete societal problems and promotes collective action and inclusion in novel ways within firms. Finally, research could be conducted on market and knowledge barriers to sustainable innovation given the current focus on financial and institutional barriers. Notably, bibliometric analysis provides a comprehensive view of a specific topic. However, this type of analysis has certain limitations related to the research protocol and the selection and inclusion of the final documents. The limitation of this study is related to the inclusion of only journal articles for analysis and the use of only one comprehensive citation index. In this regard, considering other citation indexes, such as the *Web of Science*, would be valuable for future studies.

AUTHOR CONTRIBUTIONS

A. Escobar performed the literature review and research design and analyzed and interpreted the data and prepared the manuscript text and manuscript edition. J. Luna conducted the literature review and research design and analyzed and interpreted the data, prepared the manuscript text and manuscript edition. A. Caraballo helped in the literature review and manuscript preparation.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS	DEFINITION
%	Percent
CO_2	Carbon dioxide
CSV	Comma separated values
Fig.	Figure
H INDEX	Hirsch index
PRISMA	Preferred reporting items for systematic reviews and meta-Analyses
SDG	Sustainable development goals
SJR	Scimago journal rank
SME	Small medium enterprises
UN	United nations
VOSviewer	Visualizing scientific landscapes: It is a software tool for constructing and visualizing bibliometric networks

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SPECIAL ISSUE: Eco-friendly sustainable management
RORIGINAL RESEARCH PAPEER

Modeling of peatland fire risk early warning based on water dynamics

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ABSTRACT

BACKGROUND AND OBJECTIVES: To minimize the potential risk of land fires, climate monitoring and hydrology characterization are crucial factors in managing peatlands. Therefore, this study aimed to investigate the relation between climate variability and water dynamics to develop a peatland fire early warning model.
METHODS: This research was conducted in an oil palm plantation located in Pangkalan Pisang village, Koto Gasib subdistrict, Siak district, Riau province, Indonesia. Herein, the observed parameters were climate and dynamics of ground water level and soil moisture, which were monitored using data loggers installed on predefined representative locations and distributed over three blocks of 30 hectares in the palm oil plantation research site. Thus, the peat fire early warning model was developed based on the relation between peat water dynamics and the recorded history of peat fire events.
FINDINGS: Herein, a recession curve analysis of soil moisture and ground water level revealed the relation between soil water dynamics and local climate. Consequently, this study found that soil moisture was the suitable parameter to estimate peat fire risk owing to its predictability. Furthermore, this study has identified a threshold of low and high peat fire risk in the area with less than 104 percent and 129 percent dry weight of soil moisture content, respectively. Afterward, this soil moisture criterion was transferred into precipitation value to develop a peat fire early warning model for estimating the days left before a high peat fire risk status was attained based on the latest daily rainfall rates.
CONCLUSION: This study has developed a simple peat fire early warning model using daily precipitation data. The accurate estimation of countdown days to peat fire susceptibility status in an area would enhance fire mitigation strategies in peatlands.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
47	10	4

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INTRODUCTION

Indonesia's peatland of about 13,430,517 hectares (ha) is the fourth largest area after Canada, Russia, and the United States (Page *et al.,* 2002). This country's peatland area is distributed among its four main islands: Sumatera (5,850,561 ha), Kalimantan (4,543,362 ha), Papua (3,011,811 ha), and Sulawesi (24,783 ha) (Anda *et al.*, 2021). This peatland has long become an essential part of ongoing agriculture and economic development in Indonesia and its neighboring country, Malaysia (Evans *et al.,* 2019). However, since peatland cultivation poses high environmental risks, such as peat fire, global climate change, and land degradation, it must be closely monitored and regulated to eliminate its negative impacts (Page *et al.*, 2011; Turan and Turgut, 2021; Rodelo-Torrente *et al.*, 2022). From the 1990s, various scales of peat and forest fires have been recorded in Indonesia (Miettinen *et al.*, 2012). From 1997–2015, tropical peat fires in South East Asia were estimated to release about 0.8 to 9.43 Gigaton carbon dioxide (Gt CO_2) into the atmosphere, which was equivalent to ~30 percent (%) of the estimated global fossil fuel total emission in 2020 (Horton *et al.*, 2022). Therefore, increasing peatland cultivation could further raise the potential risk of peat fire because the drained peatland would expose the highly flammable carbon material. Additionally, peat fire would trigger an irreversible peatland degradation that contributes to large-scale anthropogenic ecosystem disruption, which in turn potentially leads to local and regional economic losses and health problems (Pribadi and Kurata, 2017; Herdiansyah and Frimawaty, 2021). Thus, to minimize the risk of peat fires, the Indonesian government has regulated the maximum depth of cultivated peatland ground water level (GWL) to 40 centimeter (cm.) However, determining the optimal GWL depth for cultivated peatlands with varying peat types is difficult because of its diverse peat soil physical properties (Taufik *et al.*, 2015). Moreover, actual peat water content depends on water level while soil capillarity influences peat moisture, especially during the dry season (Moyano *et al.*, 2013). Longer drought periods, such as El Niño period, increase the chance of peat fire occurrences. During the 2015 El Niño in Indonesia, fires occurred at about 8,500 km^2 of peatland in Sumatera and Kalimantan, including commercial plantations, small farmer lands, and degraded peatlands (Taufik *et al.*, 2019). Hence, the implementation of an early warning system (EWS) emerges as a pivotal strategy for effective mitigation of peat fire risk (Prasasti *et al.*, 2013). EWS helps identify high fire-risk locations so that earlier mitigation planning can be applied. Nugroho *et al.* (2019) proposed a peat fire EWS utilizing the wireless sensor network with three parameters, namely oxygen concentration, soil moisture, and ambient temperature. The system employed a web interface to display the spatially distributed predicted area that was vulnerable to fire risk to assist stakeholders in establishing a mitigation action plan for the targeted area. Meanwhile, Spessa *et al.* (2018) developed toward a fire early warning system for Indonesia (ToFEWSI), a peat fire EWS model based on climate and hydrology data to predict fire occurrences and mitigate their impact in the Riau province of Indonesia. Another peat fire EWS based on satellite imageries for sustainable palm oil plantations in Indonesia was developed by Yulianti *et al.* (2014). Other peat fire EWS, such as the probabilistic early fire warning system (ProbFire), was developed for Indonesia by Nikovonas *et al.* (2022) based on seasonal drought prediction analysis. The majority of the previously published EWS utilized satellite imageries as the main data input, and hence, focused on the identification of the spatial distribution of highly susceptible areas to peat fire. Depending on the satellite data used, these satellite-based EWS could have a very large identification scale that might reduce the efficiency and effectiveness of planned mitigation actions. Although exceptions should be made for the work by Nugroho *et al.* (2019), it should be noted that the use of specific hardware (sensors) and software systems could further complicate and increase the cost of EWS implementation and maintenance, especially for large-scale implementation. Therefore, this research offers a peat fire EWS model based on continuously monitored peat water dynamics. The detailed information on peat water dynamics at a field level would enhance the understanding of its influence on peatland biophysical characteristics and the effect of local climate variability on soil moisture and GWL dynamics, including its correlation to peat fire susceptibility. Moreover, this research specifically addressed a prevailing research question of the drought intensity level that will increase peat fire risk. Therefore, the current study aims to develop a EWS model to estimate drought period length in relation

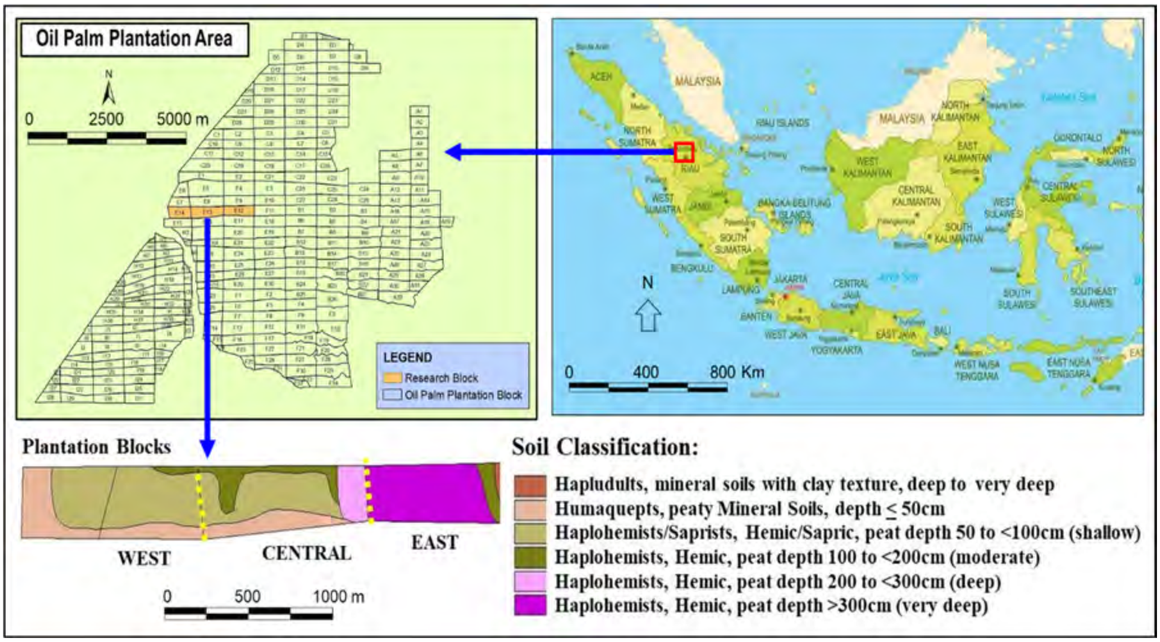

Fig. 1: Geographic location of the study area and the soil classification in Pangkalan Pisang village, Koto Gasib, Siak, Riau Province in Indonesia

to the increasing peatland fire susceptibility. This information could help decision makers to mitigate peat fire and its negative impacts on the surrounding environment. This study was conducted in a palm oil plantation in Pangkalan Pisang village, Koto Gasib subdistrict, Siak district, Riau province, Indonesia during 2021–2022.

MATERIALS AND METHODS

This study was conducted in a palm oil plantation in Pangkalan Pisang village, Koto Gasib subdistrict, Siak District, Riau Province, Indonesia during 2021–2022. The site is a freshwater topogenous peatland dominated by shallow (<3 m) peat depth located within the Gasib and Siak River peat hydrological area. Moreover, the Gasib-Siak peat hydrological area is a nonpeat dome region that covers about 3.487 hectares (ha) of peat area. The Gasib River, a tidal river with about 1.5 m magnitude, is located west of the study region and is the plantation drainage estuary. Three existing plantation blocks, each of about 30 ha (300 m x 1000 m), were selected as a water dynamic monitoring site. Fig. 1 presents the location of the three plantation blocks and the soil classification based on soil taxonomy (Soil Survey Staff, 2014). The peat soil depth in the study site varies between 50 cm and 300 cm (shallow to very deep) while the peat decomposition level is between Hemic and Sapric (moderate to highly decomposed peat soils).

From 2011 to 2019, the local average monthly precipitation data in the study area showed a wet climate with more than 2,500 mm in annual precipitation. Bimodal rainfall seasonal patterns with two distinct periods of high precipitation were identified throughout the year; one occurred during April while the other around November. Moreover, observed air temperatures were between 26.64 and 28.40˚C while relative air humidity were between 36.13% and 61.01%. The potential evapotranspiration (PET), calculated using the Penmann method, fluctuated relatively constant throughout the year with an average of about 82 mm (Penman, 1948). The highest PET value was recorded during March at 91 mm while the lowest was identified in December at 71 mm. Continuous water dynamics monitoring was performed using three water level loggers, one soil moisture logger, and one automatic weather station. The water level loggers were installed at the center of each block while the soil moisture logger was installed at the center of the East Block with the recording interval of each automatic data logger set to 30 minutes (min.). Soil Moisture Content (SMC) observation was exclusively conducted within the East Block because of several factors that include a deeper peat soil layer, a higher degree of peat decomposition, and the more distinctive presence of mineral soil compared to the other two research blocks. The weather station was located at 0.674929˚N and 101.733261˚E, about 3 km south of the research blocks, and was set to record data on a daily interval. The GWL and SMC recession rates were analyzed based on recorded data using the recession curve derived from Eq. 1 (Toebes *et al.,* 1969):

$$H_t = H_0 * exp^{(-k \cdot t)} \quad (1)$$

Where, H_t is the GWL or SMC at time *t*, H_o is the initial GWL or SMC, *k* is the recession constant, and *t* is the time interval.

The peat fire early warning of this study was modeled using two different methods: simple linear regression and the deterministic model based on the simulated SMC. Also, the simple linear regression model considered a correlation between precipitation that was represented by an antecedent precipitation index (API) and soil moisture recession rate during a no-rain days period. The API was calculated using Eq. 2 (Koehler and Linsey, 1951):

$$API = \sum_{t=-1}^{-d} R_t k^{-t} \quad (2)$$

Where, R_t is rainfall during period *t*, *k* is the decay constant, and *d* is the considered number of antecedent days. Meanwhile, the simulated SMC for deterministic modeling was calculated based on the equation that was developed by Georgakakos and Baumer (1996). SMC for each unit area was estimated based on the surface soil water balance at a certain soil depth D (i.e., a rainfall storage zone) that is later reduced by evapotranspiration and soil drainage processes over time. The SMC simulation formulas are presented in Eqs. 3, 4, 5, and 6 (Georgakakos and Baumer, 1996).

$$W_{(t)} = W_{(t-1)} + INF_{(t)} - PET_{(t)} - PER_{(t)} \qquad W_{(t)} < W_{max} \quad (3)$$

$$INF_{(t)} = R_{(t)} \left(1 - \frac{W_{(t)}}{W_{max}}\right)^m \quad (4)$$

$$PERC_{(t)} = K_S \left(\frac{W_{(t)}}{W_{max}}\right)^{3+\frac{2}{\lambda}} \quad (5)$$

$$W_{(t)} = \left[\theta_t - \theta_\tau\right] D \quad (6)$$

Where, $W_{(t)}$ is daily SMC (mm), $W_{(t-1)}$ is daily SMC before t (mm), $INF_{(t)}$ is daily infiltration (mm), $R_{(t)}$ is daily rainfall (mm), W_{max} is the maximum soil water holding capacity (mm), m is the infiltration constant, $PET_{(t)}$ is the daily evapotranspiration (mm), $PER_{(t)}$ is the daily percolation (mm), *Ks* is the hydraulic conductivity (m/s), *l* is the soil pore index based on the soil layer structure, qt is the saturated water content (m^3/m^3), qt is the water content (m^3/m^3), and D is the soil depth (m). This study specifically used SMC in the unit of percent dry weight to correlate the field data with peat fire risk which was calculated using Eq. 7 (Moorberg and Crouse, 2021):

$$SMC_{w/w} = \frac{SMC_{v/v}}{BD} * 100, \quad (7)$$

Where, $SMC_{w/w}$ is the soil moisture content based on dry weight (%), $SMC_{v/v}$ is the soil moisture content based on volume (%), and BD is the soil bulk density in dry weight per volume (gr/cm^3).

RESULTS AND DISCUSSION

Ground water level dynamic

Fig. 2 depicts the high temporal dynamics of GWL observations in the eastern, central, and western blocks from January to December 2021. Recorded data for the eastern block showed that the GWL reached a maximum of 107.9 cm/30 min on June 6, 2021, at 15:00 and a minimum of 28.2 cm/30 min on April 22, 2021, at 6:30. The average GWL in the eastern block during the observation period was 66.9 cm/30 min.

Recorded data for the central block indicated that the maximum GWL of 92.70 cm/30 min was reached on February 27, 2021, at 15:30 while the minimum of −3.10 cm/30 min was recorded on April 22, 2021, at 6:00. The average GWL for the central block during this period was 37.81 cm/day. Similarly, recorded data from the western block showed that the maximum GWL of 117.5 cm/30 min was detected on March 6, 2021, at 14:30 while the minimum GWL at 11.0 centimeter per minute (cm/min) was reached

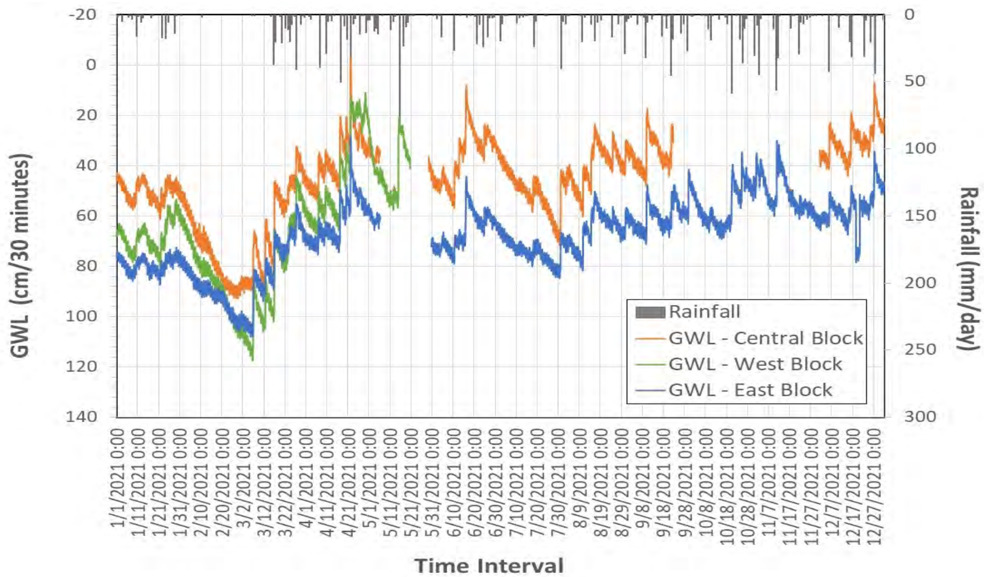

Fig. 2: Rainfall and ground water level dynamics in the eastern, central, and western Block recorded from January 1 to December 31, 2021

on April 29, 2021, at 9:30. The average GWL for the western block during this period was 65.7 cm/min. Recorded data from the three research blocks (Fig. 2) shows that GWL in the study area was highly fluctuated based on the rainfall pattern throughout the year. Kurniasari *et al.* (2021) stated that rainfall greatly influenced GWL in peatland areas through direct infiltration. Almost all of the precipitated water directly infiltrated into the peat soil because of its high hydraulic conductivity, specifically, at the peat soil surface (Wösten *et al.*, 2008). GWL in peat areas approaches the surface during the rainy season and decreases by approximately 30 cm during the dry season (Cobb and Harvey, 2019). Further decreases of over 150 cm soil depth could be reached under extreme conditions, such as during El Niño (Rossita *et al.*, 2018). Rainfall has been known to strongly influence the increasing GWLs at various locations in the Kampar Peninsula of Riau, Indonesia (Maryani *et al.*, 2020). The average GWL during the dry year of 2015 was −73 cm, with variations ranging from 1 cm to −171 cm (Wakhid *et al.*, 2019). Meanwhile, the GWL recession curve analysis of the longest no-rain day's period between January 28 and March 6, 2021, showed a substantial coefficient of determination for the eastern, central, and western blocks at 0.9428, 0.9486, and 0.9691, respectively. The curves tend to be relatively stable during the dry season possibly due to the absence of rainfall, previous water levels, and saturated aquifer thickness (Hussain *et al.*, 2022). Furthermore, the GWL recession curve data analysis for the eastern block, recorded from January 28 to March 6, 2021, indicated a recession rate of 6.99 mm/day with a total decline of 26 cm over 37 days and 4.5 hours. The maximum GWL was 175 cm while the minimum was 18.50 cm, with an average of 69.21 cm. Moreover, the central block GWL recession curve, recorded from 28 January to 27 February 2021, showed a recession rate of 14.32 mm/day with a total decline in GWL of about 44 cm over 30 days and 17.5 hours. The maximum GWL was 92.70 cm while the minimum was −12.80 cm, with an average of 37.81 cm. Similarly, the western block GWL recession curve, recorded from 28 January to 6 March 2021, showed a decline of 57.8 cm over 36 days and 23 hours with a recession rate of 15.64 mm/day. The maximum GWL was 117.50 cm while the minimum was 11.00 cm, with an average of 62.90 cm. Overall, GWL monitoring data showed that the recession rate for the central and western blocks was greater than for the eastern block. The rise and fall of the peat water table depend on the balance between rainfall, evapotranspiration, and groundwater flow. The water table gradient tends to be steeper near the dome boundary, where water flow is faster (Cobb *et al.*, 2017). Naturally, for tropical peatlands, the water table is always close to

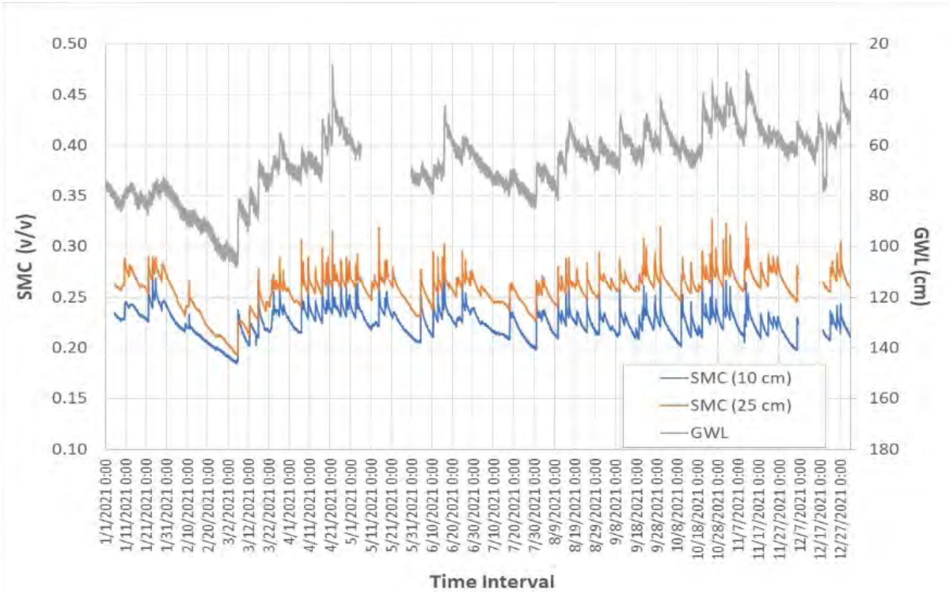

Fig. 3: Comparison between ground water level (GWL) and soil moisture content (SMC) dynamics in the eastern block during January 1–December 31, 2021

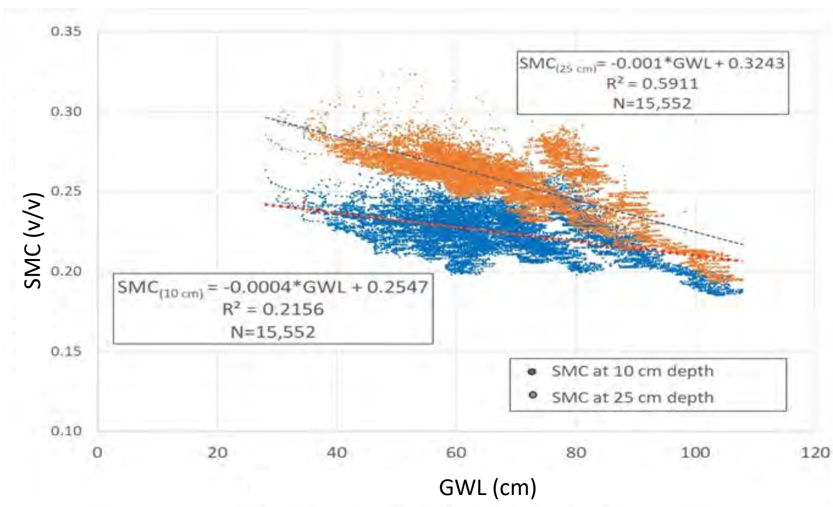

Fig. 4: Linear correlation between ground water level (GWL) and soil moisture content (SMC) data at 10 cm and 25 cm peat soil depth

the surface and its fluctuations in peat surfaces are found to be uniform (Cobb and Harvey, 2019).

Soil moisture dynamic

The GWL and soil moisture dynamics in peatland exhibited considerable fluctuations over time (Fig. 3). Analyzing the relation between GWL and SMC in the peatland surface layer revealed a relatively strong correlation between the two variables (R^2 = 0.59) at a depth of 25 cm. However, the correlation was weaker (R^2 = 0.22) at a depth of 10 cm (Fig. 4) compared to that at a depth of 25 cm. Previous studies noted that a shallow water table is commonly observed in peatlands during the rainy season

(Moyano *et al.*, 2013). Under these conditions, the actual SMC depends on the GWL, thus leading to a potentially strong correlation between GWL and SMC. The weaker correlation between GWL and SMC at a depth of 10 cm can be attributed to the reduced capillary potential of peat soil as it moves further away from the GWL. This finding aligns with the study conducted by Nugraha *et al.* (2016) in which they reported a decrease in capillary potential and consequently, a decrease in SMC with an increasing distance from the GWL. Furthermore, peat soil maturity positively influences capillary potential. At the research location, where peat maturity is sapric to hemic, water movement during no-rain day periods could be largely influenced by capillary potential. Additionally, capillary water plays a role in replacing the evaporated water at the upper layers (Yazaki *et al.*, 2006). Moreover, the weak correlation between GWL and SMC at the peat surface layer of 10 cm depth suggested that using GWL as an indicator to assess peatland fire potential could be less appropriate. Instead, a variable representing moisture conditions (i.e., SMC) could be more representative in capturing the peatland conditions related to fire risks (Prat *et al.*, 2013).

The measurements of peat surface SMC over one year from January to December 2021 ranged from 0.1848 to 0.2908 m^3m^{-3} or approximately 108.7% to 171.1% weight-to-weight ratio (w/w) at a depth of 10 cm and from 0.1928 to 0.3264 m^3m^{-3} or approximately 160.7% to 272.0% w/w at a depth of 25 cm. Meanwhile, the lowest average SMC occurred in February and March 2021, which were approximately 0.2154 m^3m^{-3} or 126.7% w/w at a depth of 10 cm, and 0.2342 m^3m^{-3} or 195.2% w/w at a depth of 25 cm. In this context, surface SMC was the primary determinant of peatland susceptibility to burning. Frandsen (1997) found that peat or organic soil will undergo continuous or sustained burning at an SMC range of 104%–129% w/w. In addition, Rein *et al.* (2008) explained that peat starts to ignite/burn at moisture levels >125% w/w. The critical SMC threshold for peatland fire risk is also determined by the degree of peat maturity, in which a higher maturity has a relatively low critical SMC. Azri (1999) stated that the critical SMC for peat fire ranged from 225.66% to 302.10% w/w for sapric, 216.89% to 290.38% w/w for hemic, and 311.24% to 417.76% w/w for fibric. The relation between the duration of no-rain days and SMC in peat soil surface layer was investigated through SMC data collected during periods of prolonged rainfall absence (>1 week without rain). Specifically, SMC dynamics were recorded from January 30 to February 9, 2021 (10 consecutive days without rain) and from February 11 to February 26, 2021 (16 consecutive days without rain). Linear regression analysis results showed a substantial negative linear relation between the duration of no-rain days and SMC at both the 10 cm (R^2 = 0.68) and 25 cm (R^2 = 0.80) soil depth. This result indicated that peat surface SMC was highly influenced by climate factors, particularly, rainfall; the longer the absence of rainfall, the lower the peat surface SMC, as described by the generated equations in Fig. 5. At the upper layer (10 cm depth), SMC decreased to >129% w/w after eight days without rain (Fig. 5), which is classified as susceptible-to-fire based on Frandsen's (1997) criteria.

Peat chemical characteristics are strong but indirectly influence the risk of peat fire. Irreversible peat soil drying happens as the peat hydrophilic functional groups decrease along with a decrease in peat SMC. Consequently, a longer drought season could shift dominant groups in the peat material to become hydrophobic (Winarna *et al.*, 2016). Valat *et al.* (1991) explained that the peat drying process occurs because the flexibility of humic polymer fractions drives polar functional groups to associate and interact through hydrogen bonding under extremely low moisture conditions. This molecular shift results in reoriented nonpolar groups on the outer part of the molecule, causing the organic colloid surface to have a low affinity for water (hydrophobic). Besides, Winarna *et al.* (2016) reported a positive correlation between peat SMC and the content of–COOH functional groups in which a higher–COOH content leads to increased water retention. Szajdak *et al.* (2010) stated that the most hydrophobic fractions of peat soil contain many hydrocarbon chains. This study's results suggested that the transformation of peat properties from hydrophilic (water-loving) to hydrophobic (water-repellent) should be avoided for sustainable peatland utilization and management. Hydrophobic properties occur after the peat SMC decreases beyond the irreversible drying critical limit. Dekker *et al.* (2001) explained that the critical SMC level of peat hydrophobic properties represents a transition zone in which the upper limit

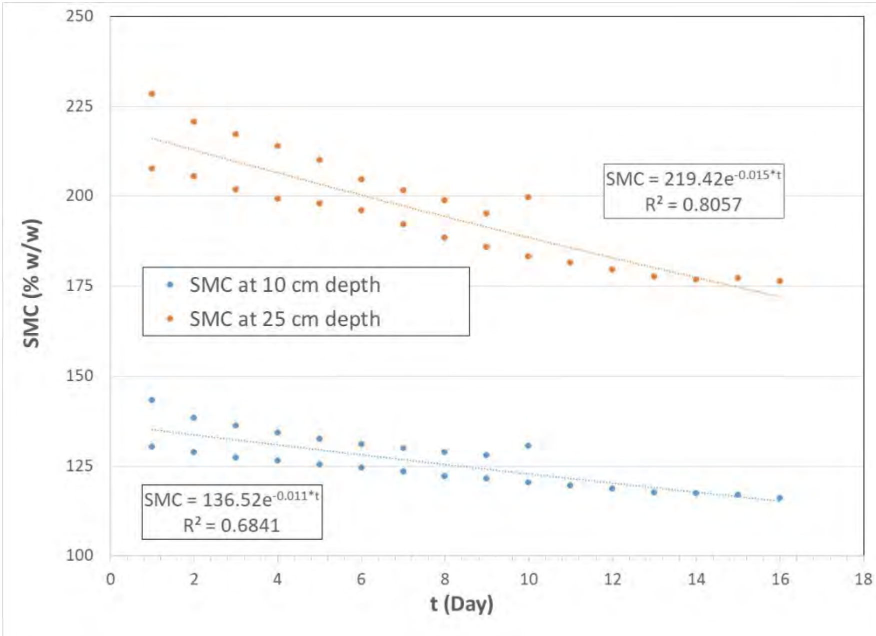

Fig. 5: Relation between the length of no-rain day with soil moisture content (SMC) at 10 cm and 25 cm peat soil depth

soil can be wetted, but the lower limit peat soil will still endure irreversible drying. Azri (1999) stated that a decrease in total acidity,–COOH functional groups, and phenolate–OH groups are signs of the irreversible drying process. Furthermore, the –COOH and phenolate–OH functional groups become nonfunctional if peat soil undergoes drought.

Peat fire risk threshold

Frandsen (1997) stated that peat will experience continuous burning under conditions of water content ranging from 104% to 129% w/w. Therefore, for this research, these values were used as the peat fire risk threshold. The lower limit (104% w/w) was set as the high fire risk threshold while the upper limit (129% w/w) was designated as the low risk threshold. Considering that the upper peat soil layer is highly susceptible to ignition compared to the underlying layers, the calibration of the peatland fire risk threshold was then applied to a series of soil moisture dynamics data at a depth of 10 cm in the eastern block as shown in Fig. 6. The graph illustrates soil moisture observations in the eastern block from January 1 to December 31, 2021, that did not exceed the high-risk threshold. Meanwhile, the lowest soil moisture value which measured 109.8% w/w, remains above the high-risk threshold of 104% w/w and occurred on March 5, 2021, due to a 40-day absence of rainfall prior to that date. Furthermore, there were approximately 25 instances throughout this period where the soil moisture exceeded the low risk threshold at 129% w/w.

Peatland fire risk early warning based on soil moisture recession curve

An SMC recession curve is one approach for predicting the peatland fire risk level by estimating the lowest SMC level that will be reached at the end of a no-rain day period. In particular, this research study used a constant declining rate to predict the SMC level. This method has been widely employed by previous studies including Romero *et al.* (2017) who analyzed the estimation of soil moisture decline rates to facilitate soil and water management. The estimation of the lowest SMC is highly dependent on the initial SMC (SMC_0) on the first day after the last rainfall event. This estimation also depends on the SMC declining rate which is greatly influenced by soil physical characteristics. The SMC_0 was determined based on the linear regression analysis between SMC and rainfall as well as the 1-day API (API_1). In this research, API_1 was selected because of its highest

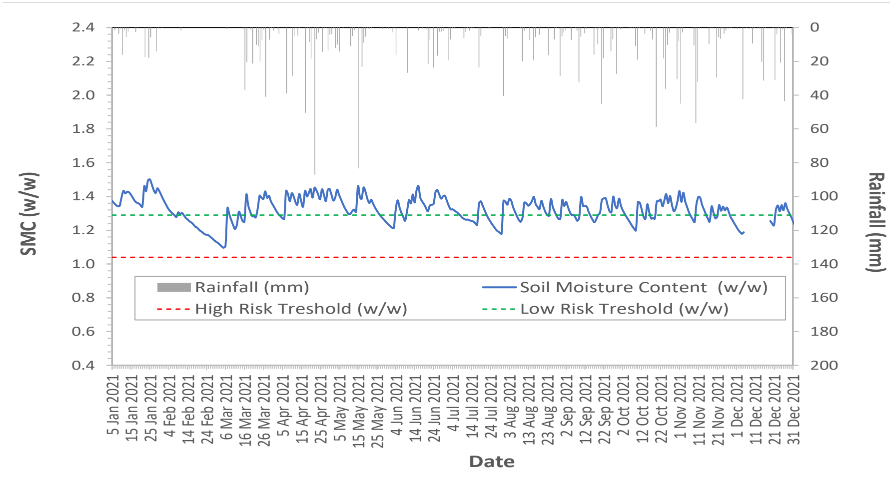

Fig. 6: Peat fire risk threshold compared to soil moisture content (SMC) dynamic in the eastern block recorded from January 1 to December 31, 2021

Table 1. Correlation between initial soil moisture content (SMC_o) and climate variables on nine different data recording episodes

Date	SMC_o (w/w)	R_i (mm)	$R_i + R_{(i-1)}$ (mm)	$R_i + R_{(i-1)} + R_{(i-2)}$ (mm)	API_1 (m)	API_2 (mm)	API_3 (mm)	PET_i (mm)	W_i (m/s)	T_i (°C)
July 03, 2021	1.324	7.00	7.20	12.60	11.80	11.80	11.80	2.20	0.46	28.40
July 19, 2021	1.371	5.00	28.60	28.60	14.30	14.30	14.30	1.80	0.36	27.80
January 04, 2022	1.231	5.00	5.00	8.60	0.00	2.70	2.90	1.70	0.29	27.00
April 12, 2022	1.371	0.20	23.40	23.40	14.10	19.00	22.00	2.10	0.17	27.80
April 22, 2022	1.382	0.40	14.60	14.60	8.60	8.60	8.60	2.10	0.19	29.10
April 26, 2022	1.402	0.00	16.80	16.80	10.20	10.20	10.20	2.00	0.12	29.30
May 05, 2022	1.435	2.00	26.00	26.40	14.60	15.70	19.10	2.00	0.31	28.40
May 17, 2022	1.398	0.20	26.60	26.60	16.00	16.00	16.00	2.20	0.13	28.50
May 29, 2022	1.371	0.20	16.00	16.00	9.60	9.60	9.60	2.20	0.41	28.50
Correlation (r)		−0.61	0.75	0.70	0.80	0.68	0.66	0.51	−0.30	0.69

correlation with SMC compared to other climate variables (Table 1). Linear regression analysis results showed a significant relation between SMC_0 and API_1 with a coefficient of determination of about 66% (Fig. 7 and Table 2). Van Liew *et al*. (2003) stated that an R^2 value greater than 0.5 is considered acceptable (Samimi *et al.,* 2023).

SMC's declining rate on a daily time interval was determined based on a regression analysis between SMC and the daily time interval during the period from January 29 to March 6, 2021. The SMC declining period was 37 days, following a rainfall event at 14 mm that occurred on January 28, 2021. The exponential equation showed the highest R^2 at 0.9718 (Fig. 8).

The formula resulted from the integration of the initial SMC_0 equation (Fig. 7) into the $SMC_{dec(t)}$ recession rate equation (Fig. 8) which was then utilized to simulate the SMC decreasing rate during the no-rain days period. Fig. 9 shows the simulated SMC validation result compared with the corresponding SMC field data measured by the Nash–Sutcliffe Coefficient of Efficiency (CE) of 0.65 (Nash and Sutcliffe, 1970).

Table 3 presents the estimated number of days required to achieve soil moisture equilibrium under low and high peatland fire risk conditions based on the previous day's rainfall scenarios. In the episode of May 17, 2022, with a precipitation of 26.40 mm or equivalent to an API_1 of 16.01 mm, the resulting initial moisture content was 1.401 w/w. Therefore, the low peatland fire risk would occur within 13 days, whereas the high peatland fire risk would occur within 43 days. Table 4 presents the data series of the previous day's rainfall interval classes that can be

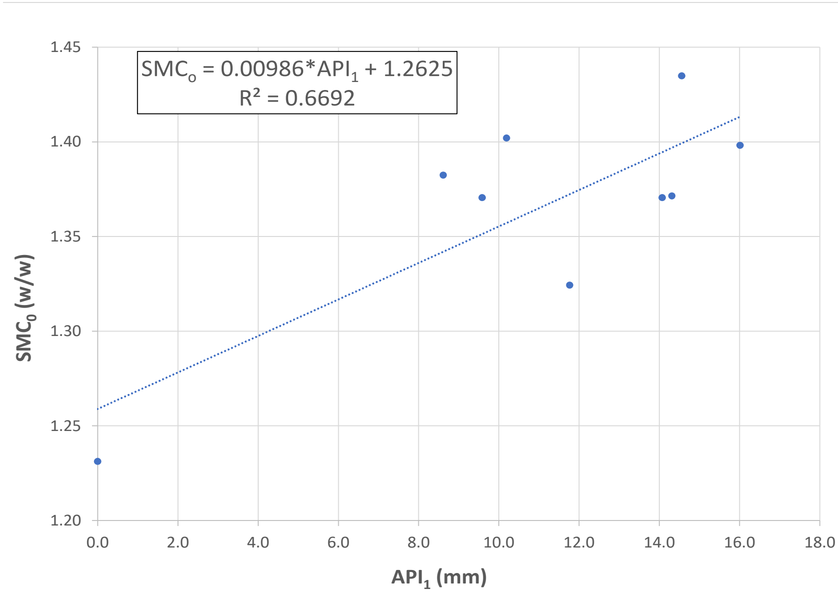

Fig. 7: Linear correlation between initial soil moisture content (SMC) and antecedent precipitation index API_1

Table 2. Regression statistics and analysis of the correlation analysis variance between initial soil moisture content (SMC_o) and 1-day antecedent precipitation index API_1

Regression Statistics									
Multiple R	0.8465								
R Square	0.7165								
Adjusted R Square	0.6692								
Standard Error	0.0347								
Observations	8								
Analysis of Variance									
	df	*SS*	*MS*	*F*	*Significance*				
Regression	1	0.0182322	0.0182322	15.16286609	0.008039927				
Residual	6	0.0072145	0.00120242						
Total	7	0.0254468							
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*	
Intercept	1.2625	0.0302	41.7451	0.00000001	1.1885	1.3365	1.1885	1.3365	
11.76669	0.00986	0.0025	3.8940	0.00803993	0.0037	0.0161	0.0037	0.0161	

utilized as criteria for estimating the time needed for soil moisture to reach low and high peatland fire risk conditions. Thus, in this study, the resulting peat fire early warning model is considered simpler than other previously developed models. Mezbahuddin *et al.* (2023) used a surface water table parameter together with SMC to predict peatland fire risk status within a 2-week timeframe.

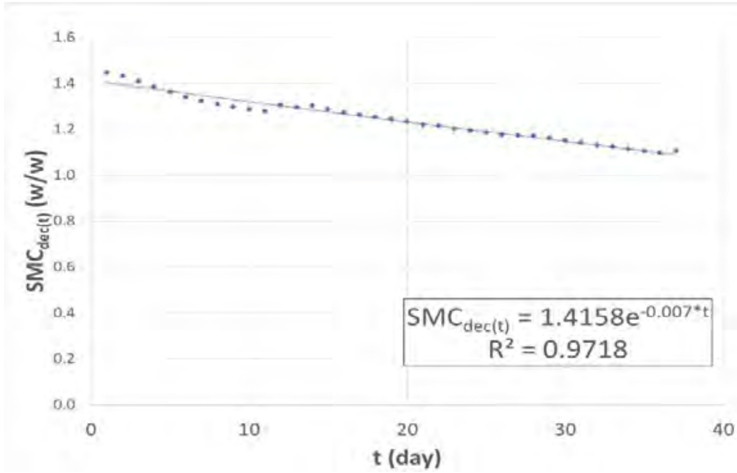

Fig. 8: Recession curve of soil moisture content (SMC) in a daily time interval

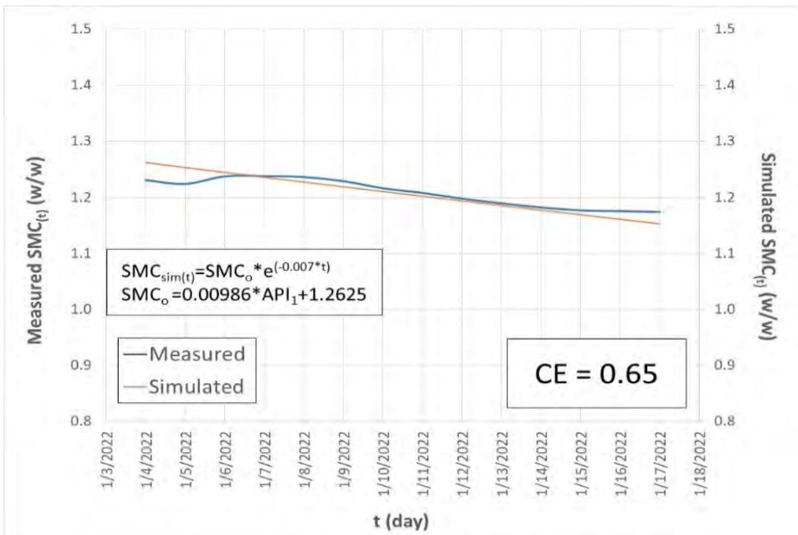

Fig. 9: Comparison between measured and simulated soil moisture content (SMC) during the no-rain period of January 4–17, 2022

Table 3: Estimation of time to low and high-risk threshold of peat fire risk based on rainfall events and the previous day's antecedent precipitation index API_1

Date	$R_{(i-1)}$	API_1	SMC_0	Time to low risk threshold (Day)	Time to high-risk threshold (Day)
May 17, 2022	26.40	16.01	1.410	13	43
May 05, 2022	24.00	14.56	1.396	11	42
July 19, 2021	23.60	14.31	1.394	11	42
April 12, 2022	23.20	14.07	1.391	11	42
July 03, 2021	19.40	11.77	1.370	9	39
April 26, 2022	16.80	10.19	1.355	7	38
May 29, 2022	15.80	9.58	1.349	6	37
April 22, 2022	14.20	8.61	1.340	5	36
January 04, 2022	5.00	0.00	1.259	1	27

Table 4: Previous day rainfall rate interval to estimate time to low and high peat fire risk

R_{i-1} (mm)	Time to Peat Fire Risk (Day)	
	Low risk	High risk
>20	11	42
10–20	3	34
<10	1	27

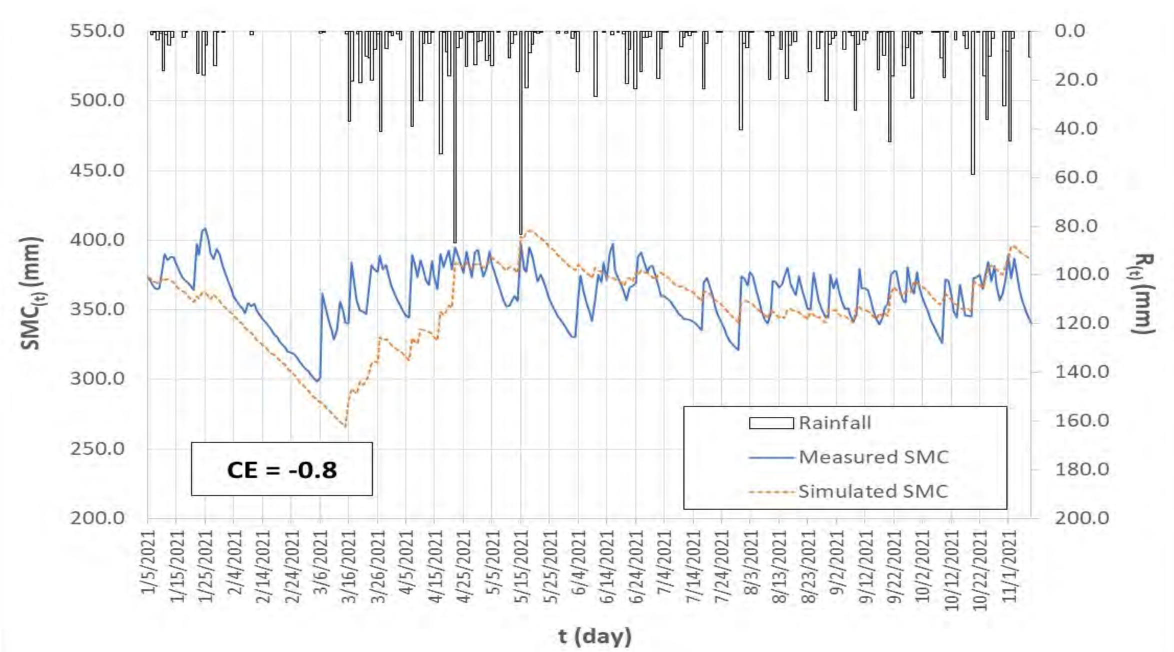

Fig. 10: Peat soil moisture content (SMC) simulation result based on rainfall data recorded from January 5 to November 1, 2021

Peatland fire risk early warning based on soil moisture content modeling

Furthermore, this research considered another SMC prediction model based on rainfall data developed by Georgakakos and Baumer (1996) to model peatland fire early warning. Fig. 10 presents the SMC simulation result using this model. Overall, the simulation results showed a tendency to underestimate SMC during the period of early January–late April but overestimate SMC between early May and late July. The Nash–Sutcliffe similarity analysis between the measured and simulated SMC showed a very low level of similarity with a CE value of −0.8. This indicates that a simple SMC prediction model based on rainfall data can still be explored to predict peatland risk to fire; however, adjustment from local SMC measurements is required to achieve better prediction precision. Moreover, this simple method is particularly useful in the area where SMC data is rare as rainfall data is commonly available.

CONCLUSION

This research has collected evidence on the influence of climate and peat soil characteristics on peatland soil water dynamics. The continuous 30-min recording interval of GWL and SMC data observation showed a consistent declining trend for both parameters within the identified no-rain day episodes in the study area. However, this study could not identify a substantial correlation between GWL and SMC, mostly, due to a higher fluctuation of GWL dynamic compared to SMC. In an agricultural peatland with artificial drainage networks, the highly fluctuated GWL dynamic was largely influenced by water loss due to seepage and groundwater flow rather than evapotranspiration. The study area observation data showed that the rate of water loss was three times higher than evapotranspiration. In addition, this study found that the SMC dynamic was more suitable for estimating peatland fire risk due to its predictability compared to that of GWL. Moreover, the recession curve method successfully modeled the daily SMC declining rate during the successive no-rain day period that represented the natural characteristic of peat soil water dynamics and the influence of the local climate in the study area. Besides, this analysis enabled the peat fire threshold identification based on the estimated daily SMC on the recorded day of peat fire events in the observation area. Furthermore, this study has identified that an area with an SMC >104% of dryweight is considered to be a high peat fire risk. Using this criterion, this study has successfully developed a peat fire early warning model to estimate the days left before the peat fire high-risk status is achieved based on the last rain-day precipitation in a dry period. The use of rainfall data to estimate days to achieve high peat fire risk could simplify the implementation of this peat fire early warning because rainfall data is commonly available compared to SMC data. While the study area might represent the general environmental conditions of tropical peatland, implementation of this model in other peatland areas would require a further validation process to accommodate differences in climate and peat soil characteristics. Particularly in Indonesia, an official directive to incorporate this validated peat fire early warning model into the already established compulsory requirement to monitor daily rainfall in a private palm oil plantation would enhance peat fire mitigation at the national level.

AUTHOR CONTRIBUTIONS

B. Kartiwa executed the experimental design, analyzed and interpreted the data, engaged in modeling, drafted the manuscript text, and participated in reviewing and finalizing the manuscript. A. Dariah performed the literature review, compiled and interpreted the data, manuscript preparation, review and finalization. Suratman compiled and interpreted the data, drafted the manuscript text, participated in reviewing and finalizing the manuscript. Maswar performed the literature review, compiled and interpreted the data, review and finishing the manuscript. S Nurzakiah involved in the field experiments, compiled the original data preparation. N. Heryani prepared the literature review, interpreted the data, original draft preparation, review and finishing the manuscript. S.H. Adi performed data analysis, involved in manuscript review, and contributed to the finalization of the manuscript. H. Sosiawan conducted the literature review, drafted the initial manuscript, interpreted the data, engaged in manuscript review, and played a role in the finalization of the manuscript. P. Rejekiningrum participated in the literature review, interpreted the data, contributed to the preparation of the original draft, took part in manuscript review, and assisted in finalizing the manuscript. N.L. Nuraida conducted the literature review, interpreted the data, participated in manuscript preparation, contributed to manuscript review, and played a role in finalizing the manuscript. I. Lenin helped in the literature review, preparation and review of the manuscript. C. Tafakresnanto participated in the preparation, review and finalization of the manuscript.

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CONFLICT OF INTEREST

The authors declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
API	Antecedent Precipitation Index
BD	Bulk Density
CE	Coefficient of Efficiency
cm^3	Square centimeter
Cm	Centimeter
COOH	Carboxyl group
D	Soil depth
E	East
Eq	Equation
EWS	Early Warning System
G	Gram
GWL	Groundwater Level
$Gt\ CO_2$	Gigaton Carbon Dioxide
Ha	Hectare
INF	Infiltration
K	Recession constant
Ks	Hydraulic conductivity
Km	Kilometer
M	The infiltration constant
m^3	Cubic meter
Min	Minute
Mm	Millimeter
N	North
OH	Hydroxide group
PER	Percolation
PET	Potential Evapotranspiration
ProbFire	Probabilistic fire early warning system
R	Correlation
R	Rainfall
R^2	Coefficient of determination
SMC	Soil Moisture Content
SMC_o	Soil Moisture Content Initial
SMC_{dec}	Soil Moisture Content declining
S	second
T	time
T_i	Temperature
ToFEWSI	Towards a Fire Early Warning System for Indonesia
v/v	volume-to-volume ratio
w/w	weight-to-weight ratio
W_i	Wind speed
W_{max}	maximum soil water holding capacity
θt	saturated water content
$\theta\tau$	water content
Λ	soil pore index based on the soil layer structure

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SPECIAL ISSUE: Eco-friendly sustainable management
CASE STUDY

Adoption and implementation of extended producer responsibility for sustainable management of end-of-life solar photovoltaic panels

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ABSTRACT

BACKGROUND AND OBJECTIVES: Extended producer responsibility has been a policy tool for managing solar photovoltaic waste in European Union countries for approximately a decade. Furthermore, EPR has been widely used in many countries for electronic waste and other forms of waste management. Several studies have recommended this tool to sustainably manage solar photovoltaic waste in countries transitioning to large-scale solar energy usage. Nevertheless, implementing a policy tool varies depending on numerous factors, particularly context differences in developed and developing countries. The research on adopting and implementing this tool for solar photovoltaic waste management is limited in developing countries. Bangladesh requires appropriate regulations to manage the impending waste, which will soon encounter substantial end-of-life solar photovoltaic panel volumes. Therefore, this study investigated the adoption and implementation of the extended producer responsibility policy tool within the context of Bangladesh.
METHODS: A comprehensive literature review was conducted to identify the enabling and challenging factors influencing the implementation of this tool. Subsequently, a Likert Scale-based questionnaire incorporating the enabling and challenging factors was framed. A survey targeting stakeholders in the solar photovoltaic sector was then performed. Data analysis involved univariate and bivariate analyses, and Bangladesh was selected as a representative developing country for this study.
FINDINGS: The results revealed that stakeholders in the solar PV industry significantly emphasized (mean > 3) all enabling factors associated with extended producer responsibility for adoption in their country to manage end-of-life photovoltaic panels. This observation signified the importance of adopting and implementing extended producer responsibility to manage the impending disposal of end-of-life solar photovoltaic panels. Among the enabling factors, the public expense reduction (mean = 3.97), user acceptance (mean = 3.89), eco-design encouragement (mean = 4.02), and the local recycling facility with secondary material market establishments (mean = 3.89) emerged as the most crucial factors. The solar photovoltaic waste-specific regulations (mean = 3.72), the absence of a pre-established collection network (mean = 4.20), and weak institutional capacity (mean = 4.03) were identified as challenging factors requiring special attention during this tool adoption. The inter-item correlation matrix analysis for enabling and challenging factors also demonstrated high significance. Moreover, Cronbach's alpha for enabling and challenging factors were 0.885 and 0.749, respectively. This outcome suggested a good and acceptable internal consistency level among the factors.
CONCLUSION: Adopting extended producer responsibility was essential in developing countries to ensure the sustainable management of end-of-life solar photovoltaic panels. Nonetheless, successful implementation required addressing specific domestic concerns, such as the absence of a pre-existing waste take-back system and weak institutional capacity. Regulators should also proactively take measures to leverage enabling factors, including gaining users' acceptance, reducing costs, and potentially tapping into secondary material markets. Consequently, this study can assist in formulating appropriate regulations regarding the sustainable management of hazardous end-of-life solar photovoltaic panels. The findings can be utilized in Bangladesh and other countries encountering similar challenges, contributing to environmental preservation and eco-friendly development.

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INTRODUCTION

Renewable energy (RE) is an essential alternative to fossil fuels in achieving a net-zero emissions target (Obobisa, 2022; Moghadam and Samimi, 2022), which is pivotal in mitigating catastrophic natural disasters driven by anthropogenic climate change to achieve sustainable development (Dincer, 2000; Fawzy *et al*., 2020). This motivation, coupled with the recent significant drop in panel cost and enabling government policies, has caused a tremendous upsurge in solar photovoltaic (PV) installations in recent years. A study reported a 46 percent (%) compound annual growth rate since 2000 (IRENA, 2019). Meanwhile, the average useful lifespan of solar PV panels ranges from 20 to 30 years (Faircloth *et al.*, 2019). Conversely, this exponential growth in solar PV systems has generated an impending challenge: the responsible retrieval and recycling of millions of metric tons of end-of-life (EOL) solar panels (Yu and Tong, 2021). A study by IRENA and IEA-PVPS (2016) reported that the world could accumulate 1.7 to 8 million tons and 60 to 70 million tons of waste panels by 2030 and 2050, respectively. Alternatively, addressing environmental challenges is imperative to generate green and clean energy from solar PV panels (Nasri *et al.*, 2023). Nonetheless, improper management of EOL panels leads to substantial resource losses and severe environmental damage, pollution, and public health hazards (Li *et al*., 2021; Drobyazko *et al*., 2021; Ramli *et al*., 2022). The demand for materials to manufacture new panels is also steadily rising. A dependence reduction on environmentally polluting and emission-causing primary sources can be highly achieved from 2035 onwards if the recycling of EOL panels is effectively established (Kusch and Alsheyab, 2017). Despite the positive environmental load impact, the economic viability of recycling remains unfavorable. Therefore, policies ensuring producer responsibility are vital throughout the PV industry, including EOL panels (Tao and Yu, 2015). The primary reason for failing to achieve collection and recycling targets for solar PV waste is the inadequate suitable regulations for bulk panel disposal in landfills (Oteng *et al*., 2022). A study by Li *et al.* (2021) in China emphasized the need for governments and industries to establish appropriate regulations and guidelines, outlining the responsibilities and obligations of concerned stakeholders. Another study by Kim and Park (2018) in South Korea highlighted the importance of implementing an appropriate system for monitoring, collecting, and storing PV waste. Regulations that demonstrate fixed recovery rate targets and compel manufacturers to retrieve EOL products are essential to address this issue (Salim *et al.,* 2019). Hence, extended producer responsibility (EPR) is a suitable option, and its novel operational measures increase sustainability in the PV sector (Cai *et al.,* 2019). The EPR is an environmental policy approach extending a producer's responsibility for a product throughout its life cycle, including the post-consumer stage (OECD, 2001). These producers include manufacturers, importers, distributors, and retailers (Kusch and Alsheyab, 2017). The EPR consists of two characteristic components as 1) Transferring either physical or economic responsibility (or both) from municipal bodies to manufacturers; 2) Allocating incentives for manufacturers to integrate environmental considerations into product designs (Rubio *et al.*, 2019). The EPR establishes a compliance mechanism for producers in collecting and recycling EOL panels. Numerous EPR objectives ensure sustainability and eco-friendly development, such as waste reduction, resource conservation, high recycling rates, waste diversion from landfills, and promoting eco-friendly product design (Majewsky *et al.*, 2021; Samimi and Safari, 2022). Particularly, European Union (EU) countries have been at the forefront of EOL solar PV panel management by applying EPR tools under the Waste Electrical and Electronic Equipment (WEEE) Directive since 2014 (Kusch and Alsheyab, 2017). These minimum targets have been set for take-back, recycling, and recovery of EOL panels based on the EU WEEE Directive, which are 60, 80, and 85%, respectively (Granata *et al.*, 2022). In the contexts of China (Yu and Tong, 2021), India (Jain *et al.,* 2022), Australia (Majewski *et al.,* 2023), and the United States of America (USA) (McElligott, 2020), the EPR implementation or similar policy tools for the sustainable management of growing EOL solar PV panel volumes has been recommended. The EPR implementation differs significantly due to social, economic, and technological differences. For example, Nigeria introduced EPR in its Electronic and Electrical Sector in 2013 to manage electronic waste (e-waste). In contrast, only 3% of importers of non-reusable WEEE had registered with the relevant regulatory authority by 2017, which produced insufficient funds for EOL management (Nnorom and Odeyingbo, 2020). Although the EPR model prevents the development and growth of the solar energy sector, its mandatory nature of whole life cycle responsibility for products imposes additional costs on manufacturers (McElligott, 2020). A suitable regulation is required considering the internal realities of each country (Jain *et al.,* 2022). Consequently, the viable use of EPR requires examination for sustainable EOL solar panel management in developing countries aiming to install large-scale PV systems. Previous studies focused on various solar PV waste aspects, including volume estimation (Domínguez and Geyer, 2017), environmental impact analysis (Maani *et al.,* 2020), life-cycle analysis (Latunussa *et al.*, 2016), and economic feasibility analysis of recycling (D'Adamo *et al.*, 2017). Stakeholder participation is important for resolving solar PV waste (Sharma *et al.,* 2023), while stakeholder consultation has been long employed in waste management and environmental policy formulation (Kujala *et al.*, 2022). Sustainable waste management necessitates the participation and consultation of all the relevant stakeholders within the respective sector (Joseph, 2006). Otherwise, environmental policies can fail if stakeholders do not accept them (Gregory and Wellman, 2001). Therefore, recognizing stakeholders' perspectives through regulatory measures is vital when addressing the solar PV waste issue. Bangladesh was selected for this study as a representative developing country case in adopting solar PV technology using data from 2003 (Hussain *et al.,* 2013). Considering that the first solar panel batch is expected to reach EOL soon, inadequate regulations can cause the EOL panels to either be in landfills or handled by the informal sector. Both options are unsustainable and harmful to this densely populated and land-scarce country. Conversely, regulation introduction ensures the large recovery of valuable materials, such as aluminum, copper, silicon, and glass. Some studies (Tasnim *et al.,* 2022) have suggested appropriate policy formulations for the sustainable management of solar PV waste. Thus, the present study bridged the existing knowledge gap by assessing the solar PV industry stakeholders' perspectives on adopting and implementing EPR in Bangladesh. The results were related to identifying enabling factors (EFs) and challenging factors (CFs) regarding e-waste, solar PV waste, and other solid waste management. The following research questions were addressed: 1) What are the EFs and CFs concerning EPR implementation for e-waste, solar PV waste, and other solid waste management in different country contexts? 2) What are the major EFs and CFs in adopting and implementing EPR (stakeholders' viewpoints in the solar PV industry) for sustainable management of EOL solar PV panels in Bangladesh?

An extensive literature review identified the EFs and CFs related to EPR implementation in various contexts. These factors were included in a survey questionnaire for further investigation. A univariate analysis method was adopted to evaluate the demographic profiles of the respondents. The mean and standard deviation (SD) were calculated to assess the central tendency of the factors. Subsequently, Cronbach's alpha (α) determined the internal consistency of the factors as a group. Bivariate analysis was also utilized to ascertain the significance factor levels in a group, such as the inter-item correlation matrix. A noteworthy aspect of this study was identifying the major EFs and CFs to EPR implementation for the sustainable management of EOL solar PV panels in a developing country. The results of this data-driven study involving the solar PV industry stakeholders offer valuable insights into countries with similar challenges. This finding can formulate effective regulations and contribute to the existing body of literature. Meanwhile, this study was performed in Bangladesh between 2022 and 2023.

MATERIALS AND METHODS

A two-stage approach was employed to achieve the objectives of this study. Firstly, an extensive literature review was conducted to identify important EFs and CFs associated with the EPR implementation in e-waste, solid waste, and solar PV waste management across various contexts. Subsequently, a survey was performed using a questionnaire incorporating the factors to evaluate the stakeholders' perspectives within the solar energy industry in Bangladesh. Fig. 1 illustrates the methodology applied in this study.

Study area

Bangladesh has been actively installing distributed and utility-scale solar PV panels. As of the first quarter of 2022, the country had an installed capacity of 416 MW of solar PV. This value had surged to 960 MW by June 2023 (SREDA, 2023). Furthermore, an additional 1448.37 MW of electricity from 24 utility-scale solar

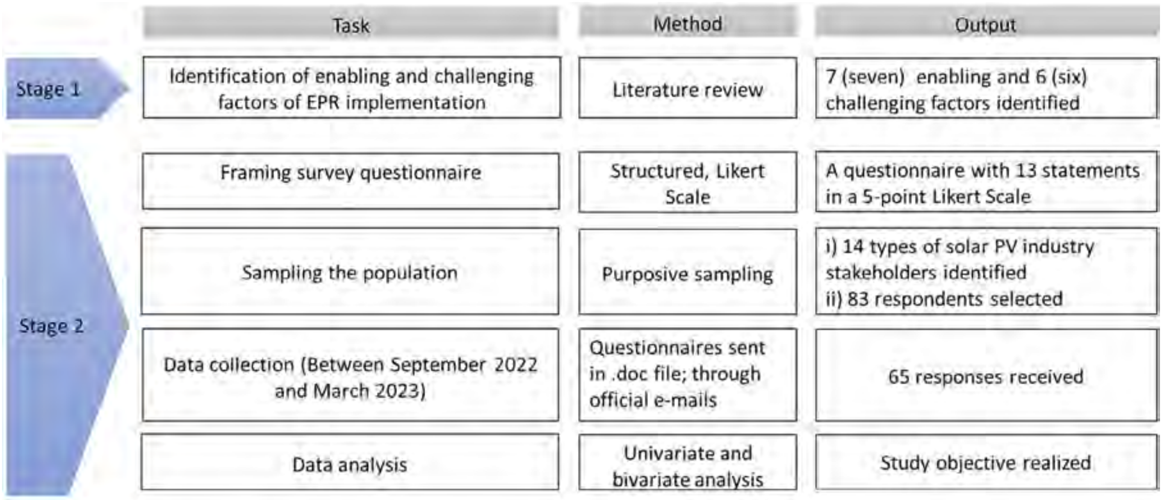

Fig. 1: Methodology applied the current study

projects has been forecasted to be integrated into the grid by 2025 (SREDA, 2022a). In addition to utility-scale installations, Bangladesh has been at the forefront of distributed solar PV adoption since 2003. The country boasts over 6 million solar home systems (SHSs), making it the largest SHS installer globally (Cabraal *et al.*, 2021). The recently drafted National Solar Energy Roadmap predicts 6.0, 20.0, and 30.0 GW of electricity production by 2041 in business-as-usual, medium, and high-case scenarios, respectively (Chowdhury, 2020). This roadmap has been drafted to increase the RE share in the national electricity generation. The country is poised to encounter a substantial EOL solar panel influx soon. Distributed solar PV systems and utility-scale plants have been scattered throughout the country, including solar irrigation pumps, rooftop solar systems, solar streetlights, and SHSs. Thus, this study encompassed stakeholders (users, implementers, distributors, and generators for solar PVs) and local government bodies responsible for waste management, e-waste recyclers, and regulators. These stakeholders were drawn from seven out of eight divisions of the country. Fig. 2 presents the study area of the survey respondents.

Factors affecting EPR implementation

One significant advantage of applying EPR is its potential for higher collection and recycling rates (OECD, 2014; Kosior and Crescenzi, 2020). For example, a waste package study in Portugal and Spain discovered increased recycling rates due to EPR (Rubio *et al.*, 2019). This benefit is particularly valuable for waste management in countries lacking physical and financial capacity or both (Tojo *et al.*, 2001). The EPR motivates related parties to incorporate materials more efficiently into their products while extending the lifespan of the products (Khawaja *et al.*, 2021). EPR holds producers responsible for the physical and financial aspects of products at their EOL (Atasu and Subramanian, 2012), producing high user acceptance. Moreover, this policy in increasing collection and recycling rates (Kosior and Crescenzi, 2020) will likely promote local recycling efforts and secondary material markets. Nevertheless, the socio-economic and technological barriers in developing countries pose challenges to deploying EPR for managing e-waste and other solid waste (Johannes *et al.*, 2021; Maphosa and Maphosa, 2022; Le Dinh *et al.*, 2022). In EU countries, the EPR tool has been effectively used for managing e-waste (Faibil *et al.*, 2022) before its application in managing EOL solar PV panels. Countries at the initial stage of solar PV recycling challenges can benefit from learning lessons and experiences with framing regulations and guidelines from EU countries (Sharma *et al.*, 2019). The requirement to shift administrative, financial, and physical responsibilities from government or local government entities to producers, manufacturers, wholesalers, or distributors (Monier *et al.*, 2014)

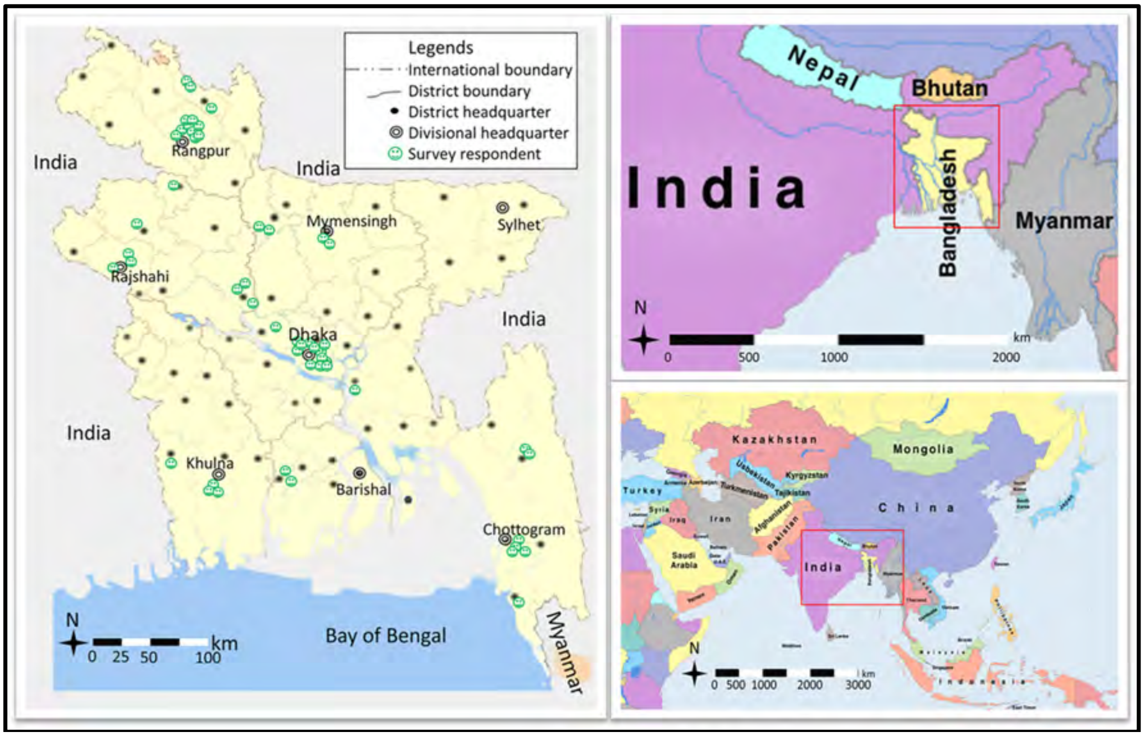

Fig. 2: Geographic location of the study survey area in Bangladesh

reduces public waste management expenses (Kosior and Crescenzi, 2020). Alongside the EFs expediting EPR, several CFs hinder its implementation. A study by Nnorom and Osibanjo (2008) on poor EPR implementations in developing countries identified insufficient legislation addressing e-waste as a fundamental issue. Meanwhile, Akenji *et al.* (2011) described that developing Asian countries encounter added complexities in e-waste management due to the prevalence of a strong informal waste sector. Unlike industrialized economies with effective waste management infrastructure, developing nations rely primarily on an informal sector employing traditional e-waste recycling methods, such as hammering and open-air burning (Gui, 2020). This informal sector involved in collecting, transporting, recovering, and disposing of e-waste hinders the effective EPR implementation (Jain *et al.*, 2022). A successful EPR implementation also necessitates a pre-established collection system due to its knowledge and expertise in expediting efficient EPR implementation (Tojo *et al.*, 2001). Developing countries often lack proper waste collection infrastructure (Gautam *et al.*, 2022; Santos and Alonso-García, 2018) and have demonstrated a lack of initiation and implementation of EPR policy (Zheng *et al.*, 2017). Furthermore, the compliance of EPR policies for waste collection and recycling imposes additional expenses on manufacturers, which are eventually passed on to end-users (Monier *et al.*, 2014). A study by Kojima *et al.* (2009) in China and Thailand revealed that producers over-reported the collected waste to receive more government support. Moreover, several concerns require continuous and vigilant monitoring, including free-riding, fair competition, illegal landfilling, and waste exports. In some instances, regulators lack the enforcement mechanisms necessary and capabilities to ensure compliance (OECD, 2014). Developing countries in Asia have encountered challenges in constructing adequate institutions and administrative capacity to effectively address the e-waste issue (Akenji *et al.*, 2011). Remarkably, recycling targets under WEEE Directives are met without recovering silver and other valuable materials considered scarce in solar panels (Ganesan and Valderrama, 2022). This situation prioritizes collection and recovery targets over full recycling. The studies above have outlined five key EPR advantages and two important factors promoting EPR adoption in EOL solar PV panels. Additionally, six CFs have been identified. These enablers and challenges of EPR implementation from different studies were used as items to frame the questionnaire for the survey in the study.

Sampling technique, population, and sample size

The solar PV sector involves numerous users and various stakeholders. Considering the EPR study based on stakeholders' consultation is a relatively complex issue, a conservative approach was adopted, particularly the purposive sampling technique. The identification and selection of the sample (stakeholders) relied on two primary sources: a study conducted by Kunz *et al.* (2014) and the stakeholder list provided by the Sustainable and Renewable Energy Development Authority (SREDA). This authority oversees expansion, regulation, monitoring, and data preservation regarding RE (including solar PV) in Bangladesh. Kunz *et al.* (2014) identified 12 stakeholder types in the EPR implementation. Alternatively, SREDA categorized stakeholders into 13 groups: government organizations (GOs), development partners, non-government organizations (NGOs) or non-government companies (NGCs), RE associations, research institutes, testing laboratories, financing organizations for RE programs, exporters, importers, suppliers, with local manufacturers of RE products or appliances, RE program/project owner/shareholder/implementer/investor in operational expenditure (OPEX) [excluding engineering, procurement, with construction (EPC) companies], and EPC companies. As of August 2022, the SREDA listed a total of 228 stakeholders. These stakeholders were categorized into 13 groups of 33, 4, 188, 3, 6, 5, 97, 8, 45, 49, 11, 147, and 176 members, respectively (SREDA, 2022b). Nonetheless, the stakeholders' roles revealed overlapping roles. For example, six members were listed under the research institute category and five in the testing laboratory category among the 33 GOs. The remaining 188 stakeholders across eight types were NGOs and companies, excluding the 33 GOs, four development partners, and three RE associations (a total 40). Only 65 were reported to have roles within the other eight stakeholder types. Given the diverse stakeholder types involved in solar PV expansion and EPR implementation, a modified section of 14 stakeholder types was included in this survey. Notably, SHS users were excluded from the present study for convenience. Instead, it focused on the organizations and institutions installing and implementing SHSs. In addition, certain stakeholder types were not included, such as development partners, producer responsibility organizations (PROs), communities, and the illegal informal sector. Consequently, the initial sample consisted of 83 stakeholders, with 65 respondents from the 14 selected stakeholder categories participating in the survey. The outcome yielded a response rate of 78.31%.

The questionnaire

The survey questionnaire comprised two parts: the first part gathered the demographic profile of the respondents. In contrast, the second part presented 13 EFs and CFs discussed in the introduction as statements. These statements were formulated using EPR experiences in e-waste and other waste management as proxies to frame the questionnaire of this study. Respondents were asked to rate their comments using a 5-point Likert Scale, where 1 represented 'least important' and 5 defined 'extremely important' for EFs (7 items) and CFs (6 items). Generally, the use of the Likert Scale waste management surveys is well-recognized. For example, Esmaeilizadeh *et al.* (2020) employed a 5-point Likert Scale to examine the challenges of municipal solid waste management in Iran. Similarly, Kabirifar *et al.* (2021) applied a 5-point Likert Scale in a close-ended questionnaire to assess the effectiveness of construction and demolition waste management in Australia.

Data collection and analysis

The questionnaires were distributed to the selected 83 respondents via their official email addresses, of which 65 respondents successfully participated. Data collection spanned six months, from September 2022 to March 2023. The Statistical Package for Social Science (SPSS) software (Version 22.0) was then used for data processing, and the analysis employed descriptive statistics and correlation analysis as the primary statistical tools. Lastly, α was calculated for the EFs and CFs to assess the consistency level among these factors.

Table 1: Background characteristic summary of the respondents

Characteristic	Category	Frequency (*n*)	Percentage (%)
Gender	Male	59	90.8
	Female	06	09.2
Service level	Top-Level	08	12.3
	Senior-Level	17	26.2
	Mid-Level	31	47.7
	Junior-Level	09	13.8
Length of service (in years)	≤ 5	20	30.8
	5–10	21	32.3
	11–15	09	13.8
	16–20	08	12.3
	≥ 21	07	10.8
Level of education	Ph.D.	05	07.7
	Master	27	41.5
	Graduate	32	49.2
	Undergraduate	01	01.5
Organization's involvement in the solar energy sector (in years)	≥ 5	23	35.4
	6–10	28	43.1
	11–15	08	12.3
	16–20	04	06.2
	≥ 21	02	03.1

RESULTS AND DISCUSSION

The respondents' background profile

Table 1 tabulates the background characteristics of the respondents. Approximately 91% were male, with most (74%) occupying top and senior service-level positions. More than 23% of the respondents possessed job experience exceeding 16 years in the solar energy sector. Approximately 49% of respondents also held post-graduate degrees, including 8% with Ph.D. qualifications. This data highlighted the successful inclusion of a diverse group of participants in the survey, ranging from junior to top-level personnel, predominantly holding graduate degrees and possessing significant service experience in the solar PV sector.

The fact that only one-ninth of the female respondents exposed were females underscored women's significant underrepresentation in the solar energy sector. In contrast, the respondents possessed a substantial experience level in the solar PV sector and a high education level, indicating their capability to comprehend and discuss issues related to implementing the EPR policy tool in Bangladesh. In addition, nearly all the respondents' organizations had more than five years of involvement in the solar energy sector, with 22% having more than 10 years. This outcome suggested that the solar PV industry in this country had matured. Fig. 3 portrays a nearly equal representation of respondents in the survey from the government (29%) and the non-government (31%) sectors in the solar PV sector. Additionally, a commendable representation of other organizations related to the solar PV sector was visible.

Fig. 4 depicts that the 65 respondents' organizations encompass 14 distinct roles in the solar energy sector. Among these roles, solar energy project implementation ranked the highest (23%), and power distribution and waste management shared the second-highest position (11%). Following closely, the roles of the respondents' organizations as regulators and exporters/importers/suppliers of solar energy products also occupied the third-highest position (8% each). This result demonstrated that respondents from various solar PV industries actively participated in this study.

Enabling factors

EFs contribute positively to a system, policy, or tool, resulting in broader benefits for a larger population. Approximately seven EFs were included in the questionnaire to elicit the perspectives of solar energy industry stakeholders (see Materials and Methods). Table 2 lists the respondents' views, in which the mean values for all items and the individual mean for each item exceed 3.62. The respondents rated five items as 'highly important' and one as 'extremely

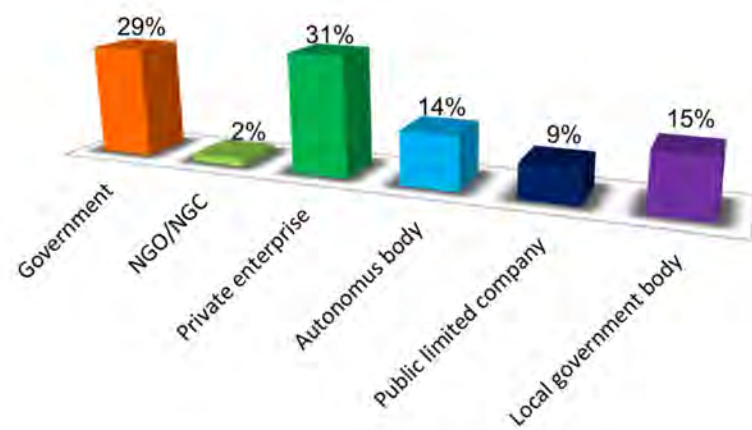

Fig. 3: The respondents' organization type

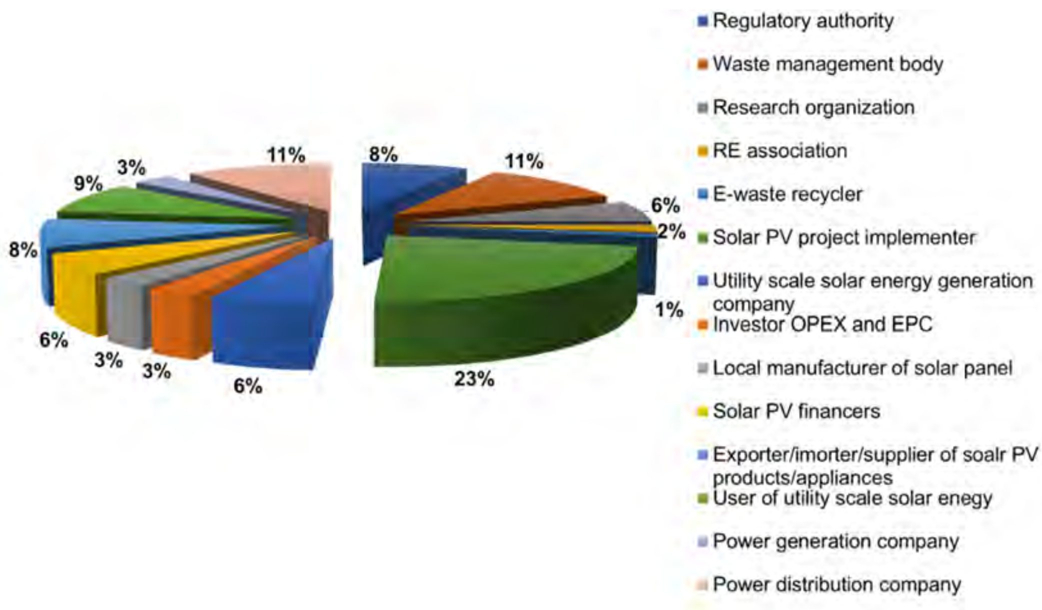

Fig. 4: The respondents' organization's role in the solar energy sector

important.' Meanwhile, the standard deviation (SD) of the item was approximately 1.0, indicating a response concentration around the mean. The α was also 0.885, suggesting a good internal consistency level among the items (0.8 ≤ α < 0.9 = good).

The implication was that the solar energy industry stakeholders placed significant importance on all the EFs of EPR. Among these factors, achieving higher collection and recycling rates was paramount. This emphasis on higher collection and recycling rates contributed to reducing environmental damage. For example, recycling EOL panels caused greenhouse gas emissions that were five times lower than landfilling (Lim *et al.*, 2022). The recycled aluminum also emitted only 4.16% of the emissions generated by extracting the same amount of aluminum from natural minerals (Xu *et al.,* 2018). In addition, recycling EOL panels prevented the depletion of scarce metals, such as silver. Silver is expected to encounter high demand by 2030, overtaking supply (Walzberg *et al.*, 2021). Globally, recovered materials can yield revenue of up to US$450 million by 2030 and US$15 billion by 2050

Table 2: Evaluation summary of the EFs for EPR application in EOL solar PV panel management (*N* = 65)

Factor	Aspect	Item	Mean	SD	Description
EFs	Achieving target (EF1)	Achieving a higher collection and recycling rate	3.68	1.047	Highly important
	Regulatory (EF2)	The practice of EPR in local e-waste management as an enabler	3.63	1.219	Highly important
	Financial (EF3)	Reduction of government expenses	3.97	0.935	Highly important
	Learning from developed economies (EF4)	The learning opportunity of EPR practice from developed economies	3.78	1.097	Highly important
	User's acceptance (EF5)	User's acceptance as they might feel relieved from the burden of EOL panels	3.89	1.062	Highly important
	Promoting eco-design (EF6)	Encouragement of eco-design in panel manufacturing	4.02	0.976	Extremely important
	Infrastructure and market (EF7)	Emergence of local recycling facility and secondary material market	3.89	0.831	Highly important
	Item mean = 3.84; α = 0.885				

(IRENA and IEA-PVPS, 2016). This yield also produces new job prospects, particularly in countries like the USA (Curtis *et al.*, 2021). Thus, the mandatory recycling promoted by EPR ensured material circularity and fostered sustainability within this sector, moving away from the linear model of material use. Adopting the EPR policy is expected to generate cost savings in managing EOL solar PV panels, as it places full life cycle responsibility on manufacturers. This adoption aligned with the findings of a study by Diggle and Walker (2020) on EPR implementation for single-use plastic packaging waste in Nova Scotia, Canada. The study estimated potential savings of C$14 to 17 million for municipalities implementing EPR. Nonetheless, in-depth investigations were required on the prospect of cost reduction in developing countries once EPR was adopted to manage EOL solar PV panels. The EPR policy adoption was likely to garner acceptance from users, as it relieved them of the burden of panel disposal after use. In addition, the EPR policy caused the creation of local recycling facilities, potentially creating a secondary material market with forward and backward linkages. This outcome was more likely because recovered aluminum and glass served as feedstocks for existing related industries in Bangladesh (Tasnia *et al.*, 2018). The respondents assigned substantial emphasis (mean = 4.02) on promoting eco-design in solar panel manufacturing (Item 6) as an outcome of EPR adoption, reinforcing expectations expressed in different studies. For example, a study in the USA context summarized that EPR inspired manufacturers to engage in eco-innovative product design, seeking a 'causal correlation' between EPR implementation and eco-innovation (Peng *et al.*, 2020). Another study in China revealed that EPR implementation led to a 35.51% increase in green innovation patents (Zhao *et al.*, 2021). Conversely, the stakeholders' expectation of eco-design panels necessitated more empirical investigation for solar panels. The significance of the results regarding EFs in this study was that the EPR initiation as a policy tool for managing EOL solar panels could produce similar positive outcomes in a developing country observed in developed regions.

Challenging factors

CFs are issues potentially hindering the implementation of a policy or system. Table 3 presents the individual means of the first four items (> 3 and < 4), while the individual means of the last two items are > 4 and < 5. The mean for all the items was 3.79 while α was 0.749, suggesting an acceptable internal consistency level among the items (0.8 > α ≥ 0.7 = acceptable).

The implications of these findings were extensive. Firstly, solar energy industry stakeholders were highly concerned regarding the collection targets for EOL solar PV panels, which were prioritized over recycling targets due to the mandatory EPR requirements. This preference for collection targets posed challenges

Table 3: Evaluation summary of the CFs for EPR application in EOL solar PV panel management

Factor	Aspect	Item	Mean	SD	Description
CFs	Achieving target (CF1)	Collection targets getting the upper hand over recycling	3.48	1.002	Highly important
	Financial (CF2)	Cost of compliance transferred onto users	3.68	0.986	Highly important
	Regulatory (CF3)	Solar PV-specific regulation might be required	3.72	1.083	Highly important
	Competition (CF4)	Informal sector of recycling as a competitor	3.63	1.069	Highly important
	Collection network (CF5)	Required the pre-existence of a collection network	4.20	1.003	Extremely important
	Institutional (CF6)	Weak institutional capacity	4.03	1.060	Extremely important
	Item mean = 3.79; α = 0.749				

to achieving a fully circular economy for waste PV panels in a developing country with limited waste management capacity. In this case, adjusted recycling targets that were not solely based on the weight of panels required establishment to encourage full recovery of materials from panels (El-Khawad *et al.*, 2022). Furthermore, the probability of transferring the compliance cost to users produced higher panel prices, which hindered the achievement of national RE targets. Therefore, the model application coordinating producers and third-party recyclers was a viable solution to mitigate producers' recycling costs (Wu *et al.,* 2019). The solar PV-specific regulation requirement suggested that separate regulation was more effective than including EPR in existing e-waste management rules (identified as a highly important CF in implementing EPR). In contrast, separate regulation involved independent management authorities, excess time, and higher costs. Policymakers should carefully consider this challenge regarding the capacity of the regulatory bodies, the size of the industry, and domestic economic realities. The informal sector also drew EOL panels due to its lower cost and ability to evade regulations, particularly in developing countries. The influence of the informal sector on regulations was disadvantageous (Gupt and Sahay, 2015), considering the complex social and environmental issues related to it (Herat and Agamuthu, 2012). A synergistic approach based on the formal and informal sector strengths could address this issue (Davis and Garb, 2015). This approach involved establishing competitive recycling plants and collection networks, raising user awareness, and enforcing environmental laws. The respondents' pre-existing collection network for implementing EPR (marked as 'extremely important') was highly significant as the weak or non-existent collection network was a reality in developing countries. In the case of EOL solar PVs, initiating voluntary product stewardship and awareness-building efforts was useful. Addressing the issue of weak institutional capacity within regulatory bodies was crucial (marked as 'extremely important' by respondents). Building up institutional capacity through training and resource allocation was necessary to overcome this challenge effectively. Thus, addressing these challenges could facilitate EPR initiation and implementation as a regulatory tool or managing EOL solar PV panels in a developing country.

Enabling factors and respondents' service level, organization type, and years of involvement in the solar PV sector

Fig. 5 reveals that solar energy industry stakeholders occupying top positions in their organizations generally give high importance to all the EFs except for EF2 (EPR practice in e-waste management as an enabler). This group prioritized a wide range of factors related to EPR adoption. Senior-level respondents placed the highest importance on EF3 (reduction of government expenses) and EF7 (emergence of local recycling facilities and secondary material markets) while still recognizing the importance of various EFs. Mid-level respondents focused the most on EF6 (encouragement of eco-design in panel manufacturing). Meanwhile, junior-level respondents placed the highest priority on all EFs except for EF1 and EF4. Most top, senior, and junior-level respondents identified the highest priority on the lower government expenses and the emergence

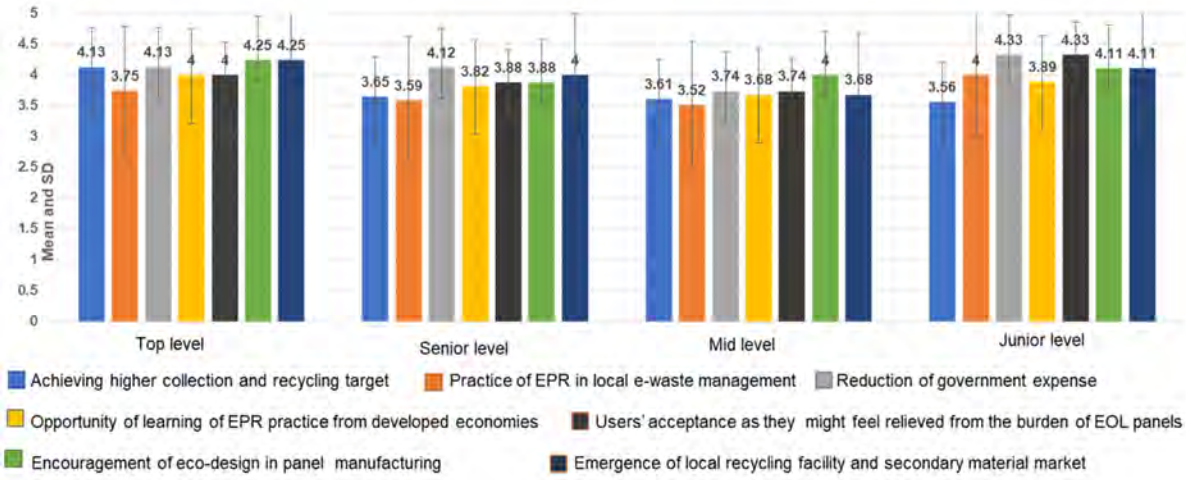

Fig. 5: The respondents' service levels and perspectives on EPR-based EFs

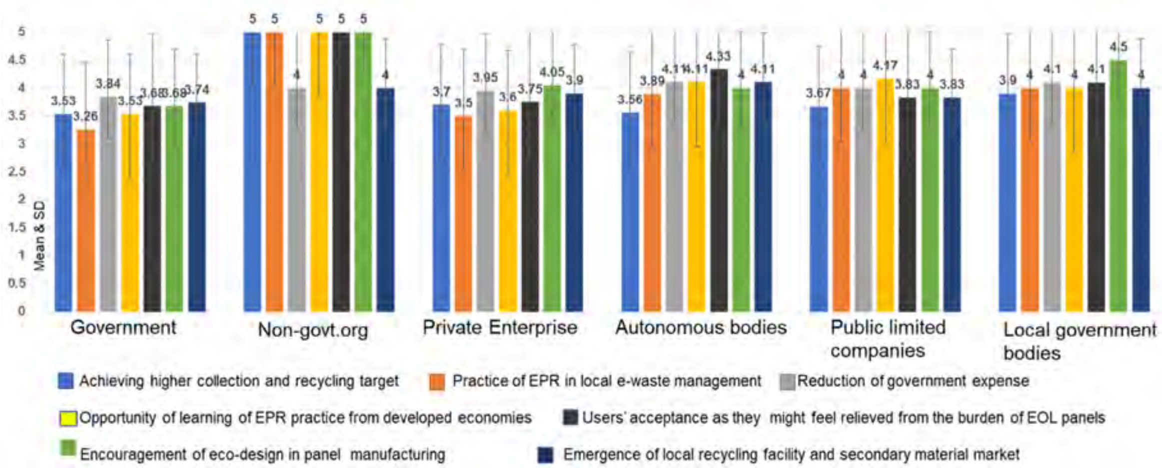

Fig. 6: The respondents' perspectives on EFs of their organization types

of local recycling facilities and secondary material markets. Therefore, initiating EPR for managing EOL solar PV in Bangladesh could guarantee these benefits at least.

Fig. 6 provides that regardless of the organization types of the respondents, high importance is attributed to all the EFs of EPR implementation in Bangladesh. Like public limited companies and autonomous bodies, local government bodies (n = 10) responsible for waste management at the provincial and municipal levels placed extreme importance on all these EFs. Conversely, private enterprises (n = 20) mostly emphasized the eco-design of solar PV panels.

Fig. 7 presents that organizations whose involvement in the solar energy sector spans over five years or more assign the highest importance to certain EFs for EPR implementation. These factors included lower public expenses in managing EOL solar PV panels, user acceptance, promoting eco-design for solar panels, and developing secondary material markets and recycling facilities. One noteworthy exception was that organizations with 16 to 20 years (n = 4) of RE sector experience expressed disagreement (mean = 2.50) with EF2. This finding underscored the necessity for a dedicated regulatory framework focused on EOL solar PV management.

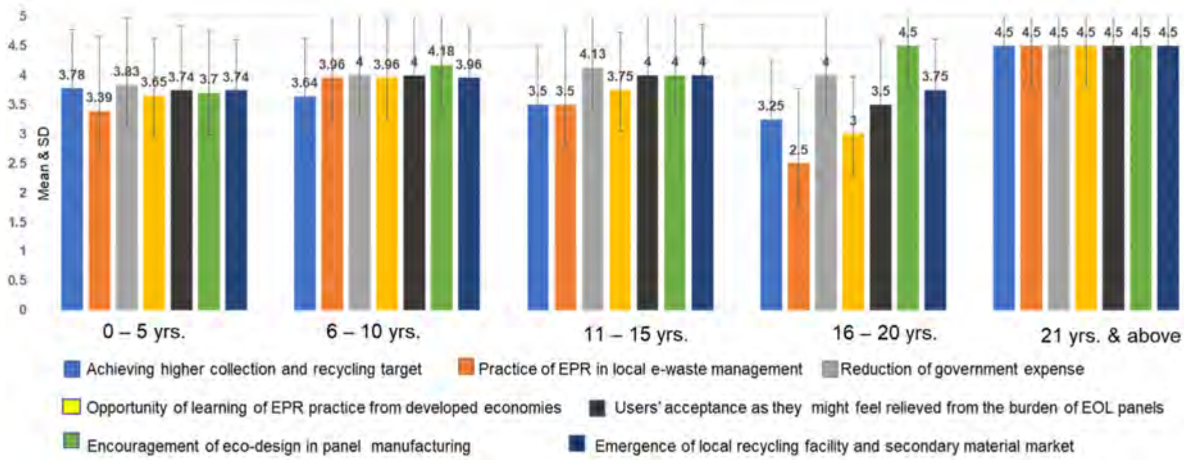

Fig. 7: The respondents' perspectives on EFs of their organizations' years of involvement in the solar energy sector

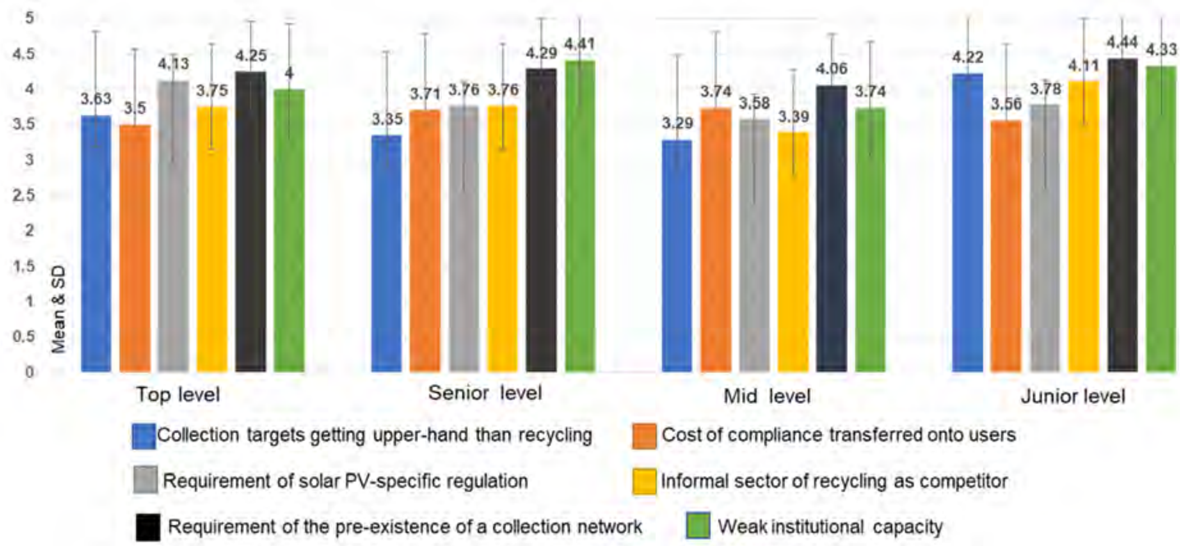

Fig. 8: The respondents' perspectives on CFs of their service levels

Challenging factors with the respondents' service level, organization type, and years of involvement in the solar PV sector

This study aimed to understand whether the service level of the respondents influenced their perceptions of the CFs associated with EPR. Fig. 8 exhibits that respondents from all service levels assign high importance to all challenging EPR factors in managing EOL solar PV panels in Bangladesh. Nevertheless, the highest degree of importance (regardless of service levels) was given to the necessity of a pre-existing collection network and weak institutional capacity as key challenges in the EPR implementation. Moreover, respondents at the highest service level (*n* = 8) emphasized that the need for specific solar PV-related regulations posed the most critical challenge in the successful implementation of EPR.

The respondents from all six organization types assigned the highest importance to weak institutional capacity and the requirement for a pre-existing collection network due to the EPR implementation challenges in Bangladesh (see Fig. 9). Additionally,

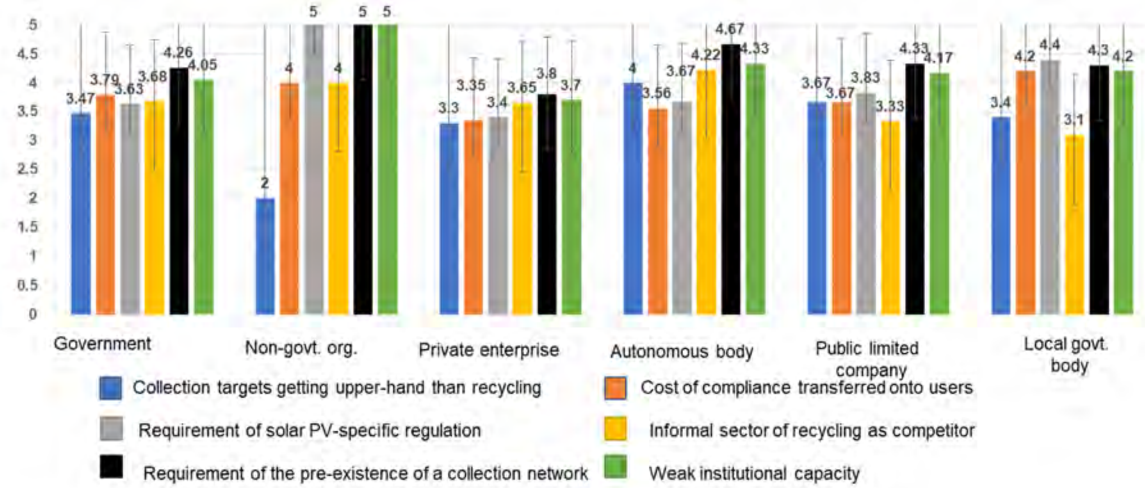

Fig. 9: The respondents' perspectives on CFs of their organization types

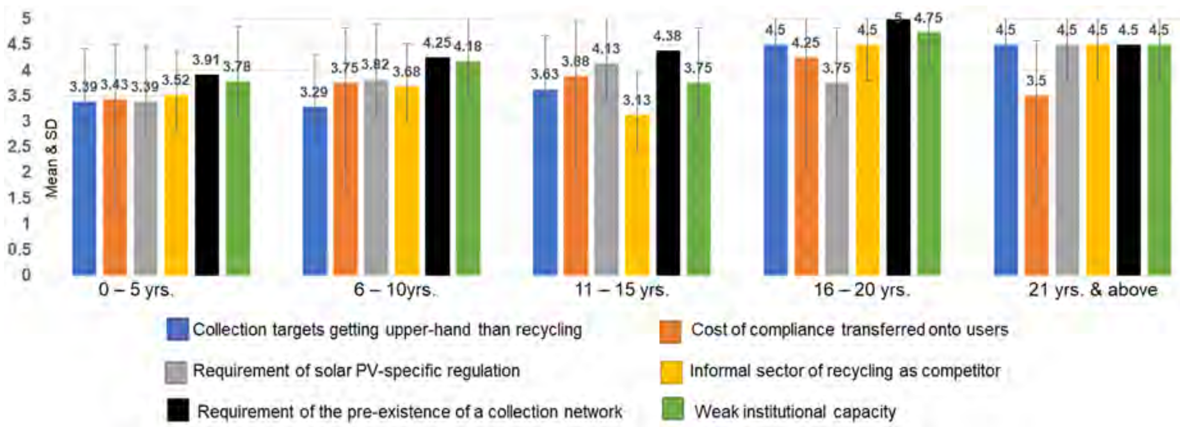

Fig. 10: The respondents' perspectives on CFs of their organizations' involvement in the solar PV sector

respondents from autonomous bodies (*n* = 9) highlighted the informal sector as a competitor to formal recycling of EOL solar PV with the highest importance. An established collection network was a prerequisite for successful EPR implementation, particularly in rural areas of Bangladesh. These findings aligned with a study by Steenmans and Malcolm (2023), which identified the absence of waste collection services in rural areas as a significant challenge in the EPR implementation for managing plastics.

Fig. 10 displays that regardless of the number of years besides involvement in the solar PV industry, the respondents generally assign importance to all the CFs associated with the EPR implementation. Nonetheless, greater emphasis was placed on the necessity of a pre-existing collection network and weak institutional capacity as CFs. The organizations with over 16 years of experience (*n* = 6) also emphasized collection targets, getting preference over recycling targets and the informal sector as a competitor. The findings on the whole reaffirmed the views expressed by stakeholders.

Inter-item correlation matrix of the factors

The inter-item correlation matrix of the EFs and CFs identified in this study. Table 4 showcases the correlation coefficients (*r*) between X_{11} with X_{12}

Table 4: Summary of the inter-items correlation (EFs)

Items	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}
x_{11}	1.000						
x_{12}	.396**	1.000					
x_{13}	.210	.134	1.000				
x_{14}	.328**	.078	.221	1.000			
x_{15}	.355**	.398**	.268*	.522**	1.000		
x_{16}	.398**	.353**	.266*	.465**	.626**	1.000	
x_{17}	1.000	.396**	.210	.328**	.355**	.398**	1.000

Note: x_{11} = Achieving higher collection and recycling rate; x_{12} = Practice of EPR in e-waste management as an enabler; x_{13} = Reduction of government expenses; x_{14} = Opportunity to learn EPR practice from developed economies; x_{15} = Users' acceptance of EPR as it relieves them from the burden of EOL panels; x_{16} = Eco-design in panel manufacturing; x_{17} = Emergence of local recycling facilities and secondary material markets; *$p < 0.05$; **$p < 0.00$.

Table 5: Summary of the inter-items correlation (CFs)

Items	x_{21}	x_{22}	x_{23}	x_{24}	x_{25}	x_{26}
x_{21}	1.000					
x_{22}	.396**	1.000				
x_{23}	.210	.134	1.000			
x_{24}	.328**	.078	.221	1.000		
x_{25}	.355**	.398**	.268*	.522**	1.000	
x_{26}	.398**	.353**	.266*	.465**	.626**	1.000

Note: X_{21} = Collection targets get the upper hand over recycling; x_{22} = Cost of compliance transferred to users; x_{23} = Solar PV-specific regulation might be required; x_{24} = Informal sector of recycling as a competitor; x_{25} = Required the pre-existence of a collection network; x_{26} = Weak institutional capacity; *$p < 0.05$'; **$p < 0.00$.

, X_{14}, X_{15}, and X_{16}; X_{12} with X_{14}, X_{15}, and X_{16}; X_{13} with X_{15} and X_{16}; X_{14} with X_{15}, X_{16}, and X_{17}; X_{15} and X_{16}; X_{16} and X_{17}. Notably, the highest correlation coefficients were between X_{14} (opportunity to learn EPR practice from developed economies) and X_{15} (users' acceptance of EPR as it relieves them from the burden of EOL panels), X_{14} and X_{16} (promotion of eco-design in panel manufacturing), and X_{15} with X_{17} (emergence of local recycling facilities and secondary material markets). Therefore, the interpretations and inferential analysis of the EFs of EPR presented in this study were considered dependable.

Table 5 denotes the *r* between X_{21} with X_{22}, X_{24}, X_{25}, and X_{26}; X_{22} with X_{24}, X_{25}, and X_{26}; X_{23} with X_{25} and X_{26}; X_{24} with X_{25} and X_{26}; X_{25} and X_{26}. Particularly, the highest significant correlations were between X_{24} (informal sector of recycling as a competitor) and X_{25} (required the pre-existence of a collection network), X_{24} and X_{26} (weak institutional capacity), and X_{25} and X_{26}. These correlation coefficients solidified the inferences and analyses of the CFs hindering the EPR adoption and implementation in managing EOL solar panels in a developing country context.

CONCLUSION

This study revealed that adopting EPR as a policy tool for managing EOL solar PV panels benefited developing countries. When implementing EPR, consideration was required for all the EFs and CFs identified in this study. Nevertheless, three EFs were more significant. These factors were accelerated users' acceptance (mean = 3.89) due to the shifting of disposal burden to manufacturers or wholesalers, a higher probability of lower government expenses (mean = 3.79) if EPR was adopted, and the potential emergence of a domestic secondary material market and recycling facility under EPR (contingent upon the existence of an industry ready to use recovered materials as feedstock). Like EFs, three challenging aspects were more crucial. Developing countries with weak institutional capacity and no existing collection network encountered challenges in fully adopting EPR. Thus, enhancing institutional capacity through awareness campaigns and motivation initiatives addressed this concern. Furthermore, implementing a solar PV-specific regulation rather than incorporating solar PV waste management into existing e-waste regulations was more effective. Conversely, regulators should consider several factors when establishing a separate law for managing EOL solar PV panels, such as capacity, resources, industry size, and implementation costs. Transferring EPR compliance costs to consumers also hindered solar PV expansion. Therefore, measures such as involving third-party recyclers, fostering coordination between third parties and producers, offering government subsidies, and providing tax exemptions were beneficial. Gaining views directly from stakeholders actively involved in the solar PV industry of Bangladesh provides valuable insights, preventing the replication of policies from developed nations and considering local realities. The findings of this study can aid policymakers in Bangladesh and countries encountering a similar challenge in managing end-of-life solar PV panels, a significant form of e-waste. Future studies should explore the issue of adopting mandatory or voluntary EPR, cost-benefit comparisons between the inclusion of solar PV waste in existing e-waste management rules, and the implementation of a separate solar PV waste-specific regulation. Consequently, examining how manufacturers reconcile compliance costs with their economic interests in a developing country context is another promising study area.

AUTHOR CONTRIBUTIONS

S.E. Kabir performed the study design, literature review, data collection, compilation, analysis, and interpretation of data along with the manuscript text preparation and edition. M.N.I. Mondal performed data validation, analysis, manuscript preparation, and edition. M.K. Islam helped prepare the manuscript and edit it. I.A. Alnaser helped prepare and edit the manuscript. M.R. Karim helped prepare and edit the manuscript. M.A. Ibrahim helped prepare and edit the manuscript. K. Sopian helped prepare and edit the manuscript. Md. Akhtaruzzaman supervised the whole work and helped prepare and edit the manuscript. All authors evaluated the results and approved the final version of the manuscript.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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ABBREVIATIONS

α	Cronbach's alpha
>	Greater than

≥	Greater than or equal to
<	Less than
≤	Less than or equal to
%	Percent
C$	Canadian dollar
n	Number
p	probability
r	Correlation coefficient
yrs.	Years
CF	Challenging factor
e-waste	Electronic waste
EPC	Engineering, procurement, and construction
EF	Enabling factor
EOL	End-of-life
EPR	Extended producer responsibility
EU	European Union
Fig.	Figure
GO	Government organization
GW	Gigawatt
MW	Megawatt
NGC	Non-government company
NGO	Non-government organization
OECD	Organization for Economic Co-operation and Development
OPEX	Operational expenditure
Ph.D.	Doctor of Philosophy
PRO	Producer responsibility organization
PV	Photovoltaic
RE	Renewable energy
SD	Standard deviation
SHS	Solar Home System
SPSS	Statistical package of social science
SREDA	Sustainable and Renewable Energy Development Authority
USA	United States of America
WEEE	Waste Electrical and Electronic Equipment

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SPECIAL ISSUE: Eco-friendly sustainable management
REVIEW PAPEER

Bibliometric analysis for sustainable food waste using multicriteria decision

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ABSTRACT

Sustainable food waste management is globally concerning, thus necessitating cutting-edge approaches and a thorough understanding. To address this complicated problem effectively, bibliometric analysis and multicriteria decision-making can be combined. Therefore, multicriteria decision-making methods have become critical tools for navigating the intricacies of sustainable solution development. This study explored the complex field of sustainable food waste management by conducting a comprehensive bibliometric analysis of multi-criteria decision uses in this field. Using bibliometric methods, a methodological examination of the scientific literature was performed to identify important trends, contributions, and gaps in research on sustainable food waste. Decision-makers can be further empowered by using multicriteria decision-making to assess interventions across various dimensions, including environmental effects, economic viability, and social acceptability, highlighting the interdisciplinary nature of this strategy and promoting interactions between researchers, decision-makers, and stakeholders. These guidelines directly followed the development of policies, business practices, and consumer behavior, indicating a more sustainable food system. The combination of bibliometric analysis and multicriteria decision-making offered a formidable instrument to reduce food waste, enhance resource efficiency, and spur progress in global sustainability initiatives in a world where sustainable behavior is crucial. The study results in decision-makers evaluating interventions and strategies holistically by concurrently considering the food waste dimension, a multicriteria model, economic factors, environmental factors, social factors, policy considerations, and technical feasibility are just some of the factors considered in this study. This analysis highlights the growing commitment to comprehensive solutions that focus not only on waste reduction but also on resource efficiency, environmental stewardship, and societal well-being as sustainable food waste management gains traction on global agendas.

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INTRODUCTION

In the last decade, food waste has become a potential problem in achieving sustainable development goals of converting food waste into new usable and marketable products (Bilal and Iqbal, 2019; Zaman *et al.,* 2021; Weekes *et al.,* 2021; Charkhestani and Yousefi Kebria *et al.,* 2022). Food is discarded at many points in the food supply chain. Products that fail to fulfill aesthetic or quality criteria are frequently wasted on farms (Ortiz-Gonzalo *et al.*, 2021). Losses may also result from insect damage or overabundance of production. Offcuts, byproducts, and goods that do not fit the exact criteria add to the waste in processing and manufacturing. In retail settings, products not sold, outdated, or have slight flaws are regularly discarded. Plate waste, over preparation, and spoiling are sources of waste in restaurants, cafeterias, and catering industries. Furthermore, families play a significant role in the food waste problem owing to spoilage, underuse, and overbuying. Large amounts of edible food are discarded worldwide. Approximately one-third of the food manufactured for human consumption is never consumed (Williams and Rangel-Buitrago, 2022). This is equivalent to disposing of trillions of dollars' worth of food annually, or several billion tons (Tomaszewska *et al.*, 2022). This transformation is one of the crucial factors for the future of society and economies in various countries. To date, multiple studies have highlighted the increased investment in processing food waste, the price of essential ingredients, food insecurity, increased costs in the supply chain, and the resulting economic losses (Boyacı-Gündüz *et al.*, 2021). This is a compelling subject to researchers, as shown by the issue of food waste from various fields of science, as evidenced by the fact that the term food waste from Scopus, Science Direct, and Web of Science has up to 370,000 scientific papers on the economic impact of food waste, technical, regulatory food waste, social, renewable energy, and the impact on the environment (Chen *et al.*, 2014; Nouri, 2022). Researchers use various methods to achieve sustainable development supported by these various fields of knowledge. The initial discussion of "Estimating Food Losses from Field to Fork on a Global Scale," published in 2011 by the Food and Agriculture Organization (FAO) of the United Nations (UN), discusses global estimates of the amount and impact of food wastage at various stages of the food supply chain and technological advances developed in processing food waste into usable products for use and sale (Ghosh *et al.*, 2016). In addition, FAO has observed various approaches to food waste recovery that consider economic, environmental and social factors. Therefore, various technological options have been developed according to each region's needs and existing conditions to minimize environmental damage, public health, and economic benefits (Surendra *et al.*, 2014; Samimi and Shahriari Moghadam, 2018; Ehzari, *et al.,* 2022). Companies or parties that use products from food waste management in the form of fertilizer, electricity, and animal feed have examples of having a low environmental impact (lower consumption of fossil fuels, use of electricity, and generated pollution) and also fulfil social values, as well as consumer concern (Donner *et al.*, 2020; Nordahl *et al.*, 2020). In this scenario, stakeholders, researchers in each field, policymakers, governments in each region, and producers collaborate to choose various technologies and methods to achieve sustainable improvement by weighing factors such as technology, the economy, ecology, and society (Caputo *et al.*, 2023; Sachs, 2012; Solangi *et al.*, 2021). Thus, decision-makers must choose indicators and simultaneously make decisions with solid origins. Choosing the best sustainable option that may lessen the negative effects on the environment while bolstering the economy and society is challenging in the current setting. Various choices, viewpoints, and indicators hinder fast and precise selection. By comparing and summarizing the results of different choices, mathematical tools can aid in finding optimal solutions to organizational difficulties. Multicriteria Decision Making Aiding (MCDMA) is a commonly used approach that determines the criteria involved in selecting decisions, limiting choices to suggest priority choices that the decision-maker has predetermined (Bortoluzzi *et al.*, 2021). To comprehend research tendencies, contributions, and gaps in sustainable food waste management, the MCDMA concept was incorporated into the analysis in a methodological and structured manner (Fusté-Forné and Noguer-Juncà, 2023). To ensure consistency with the core concept of considering many decision-making criteria, articles were carefully selected that directly addressed the relationship between MCDM and sustainable food waste management. The selected papers were evaluated based on a set of established criteria. The use of MCDMA frameworks, the incorporation of environmental, economic, and social components, and the breadth of investigation into the complexity of food waste management were all considered as part of these requirements. When the selected papers were categorized and classified according to the specific MCDM methodologies or frameworks utilized, clear tendencies in the application of various techniques were apparent. A quantitative analysis plays a crucial role in explaining these tendencies by quantifying the use of different MCDMA techniques. This quantitative method helped highlight the prevalent MCDMA methodologies and highlighted industry norms. Moreover, the articles revealed overarching themes encompassing waste reduction techniques, resource allocation, stakeholder engagement, and policy formation, as observed through the MCDMA lens. The algorithms presented in the MCDMA model are useful tools for solving complex problems in the food waste field (Angelo *et al.*, 2017). Various methods have been applied to various cases that consider many perspectives and fields of science, economics, and society, such as China (Xi *et al.*, 2010), Singapore (De Clercq *et al.*, 2017), England (Iacovidou and Voulvoulis, 2018), and Indonesia (Yunus *et al.*, 2020). The relevance and weighting of the criteria are among the variables examined and provide information on the relative weights assigned to each criterion. Cost-benefit analyses examine the aspects of investment, operations, and income from an economic perspective. When combined, environmental impact parameters focus on resource utilization, emissions, and ecological footprint, highlighting the sustainability problem. The inclusion of risk and uncertainty parameters acknowledges the erratic character of outcomes, whereas social and ethical components gauge the influence on society and ensure that choices are consistent with moral principles (Ellestad and Winton, 2022). The all-inclusive evaluation strategy incorporates stakeholder priorities, quality measures, and regulatory conformity. Understanding the interplay of these variables is crucial and often necessitates the development of novel approaches. Moreover, in the quest for environmentally responsible food waste management, MCDMA strategies are crucial and provide essential direction. Waste management approaches can be compared using performance and utility scores, leading to decisions that more effectively reduce waste, conserve resources, and reduce environmental damage (Schmidt and Laner, 2023; Samimi and Mansouri, 2023). Economic considerations inform financial viability through a cost-benefit analysis, which directs resource allocation and justifies investments in waste-reduction technology and disposal strategies (Aithal and Aithal, 2023). Decisions guided by environmental impact criteria reduce emissions, save resources, such as water and energy, and save ecosystems (Drobyazko *et al.*, 2021; Moghadam and Samimi, 2022). Decisions that consider the community's welfare, food security, and moral principles are strengthened when social and ethical considerations are considered. Choosing strategies consistent with the current infrastructure is facilitated by conducting a technical feasibility evaluation. Therefore, sustainable technologies for food waste and MCDMA are relevant areas of study and have significant potential for progress (Bolaji *et al.*, 2021). Various literature reviews have highlighted the qualitative and theoretical research on food waste, management technologies, planning for sustainable systems, foresight, and supporting economic and policy decisions regarding food waste (Thyberg and Tonjes, 2015; Ghazali *et al.*, 2021). Previously cited research, however, has not yet addressed particular difficulties, such as the most frequently used performance metrics or MCDMA models for evaluating food waste. This represents an opportunity to explore subjects through bibliometric studies. Provided they can impartially recognize patterns in research, bibliometric studies offer the advantage of systematizing research topics carefully chosen by researchers (Verger *et al.*, 2019). Another notable contribution of this study is that by researching food waste, the application of the MCDMA model can be another direction, which still needs to be used. Therefore, this bibliometric technique is considered sufficient in identifying the characteristics of the research agenda on the theme of food waste and MCDMA (Bortoluzzi et al., 2021). Therefore, based on various aspects of sustainable food waste technology and methods, this study aimed to explore the complex field of sustainable food waste management by conducting a comprehensive bibliometric analysis of multi-criteria decision uses. Moreover, scientific literature was methodically examined using bibliometric methods to identify important trends, contributions, and gaps in research on sustainable food waste. Studies were conducted at Diponegoro University from January to August 2023 to segregate sustainable food.

Exploring food waste, MCDMA methods and criteria

This section briefly reviews various studies on alternative technologies and methods for food waste in implementing sustainable development, as well as the reasons for the MCDMA method and criteria used to study sustainable development through food waste.

Identification of sustainable food waste technology and method

Identifying technologies and methods for sustainable food waste involves considering various approaches that effectively reduce food waste, minimize negative environmental impacts, produce products with marketable and usable values, and promote resource efficiency to meet FAO and Environmental Protection Agency (EPA) goals. Additionally, alternative technologies should be as realistic as possible because of the socioenvironmental effects of energy generation and use (Taghikhah *et al.*, 2019; Pouran *et al.*, 2022). Simultaneously, the limitations of selection for implementation are various indicators and the impact of various technologies on the environment and society. According to Ma and Liu (2019), sustainable food waste technology has a low cost, small impact, and produces no residue that cannot be reused (Wojnowska-Baryła *et al.*, 2020). Food waste can be analyzed from a sustainability perspective as well as from its technical characteristics (Han *et al.*, 2022). Consequently, the quantity required to satisfy market demand and its technical characteristics, such as integration with other sources, must be considered (Lee *et al.*, 2020), and the economic feasibility of energy efficiency and operational costs are crucial factors in considering the selection of products (Hoang and Nguyen, 2021). Several studies have analyzed food waste sustainably. However, gaps result from studies analyzing variables such as geography, awareness and behavior change, equity and social sustainability, infrastructure, and accessibility to make the right choices when applying food waste technologies (Bachmann *et al.*, 2022; Rejeb *et al.*, 2021). Consequently, various options are available from various sources (new technologies arise to enhance the efficacy of existing sources). The following is a list of many sustainable technologies and approaches found in the literature review to help choose each solution with increased clarity.

1. Intelligent monitoring and tracking systems and precision agriculture are based on newly developed sensors (García *et al.*, 2020). Real-time monitoring with this technology and data analytics can be used to monitor and identify waste points, improve efficiency, and reduce overall food waste (Kayikci *et al.*, 2022). Precision agriculture uses drones and data analytics to increase agricultural efficiency, reduce food waste at the production level, and optimize the use of resources in the form of water and fertilizer (Monteiro *et al.*, 2021; Raj *et al.*, 2022). These technologies use the principle of preventing food waste generation, which has the highest hierarchy in food waste technology and methods.

2. Food redistribution involves the principle of food reuse. This method involves collecting and redistributing edible foods from surplus restaurants, supermarkets, or households. Food banks are allocated to those in need for distribution to charitable institutions.

3. Insect-based conversion involves living organisms in the form of insects, such as Black Soldier Flies (BSF) or mealworm beetles, converting food waste into a high-quality protein source (Mannaa *et al.*, 2023; Varelas, 2019). The intended conversion is in the type of insects used to consume food waste, convert insects into animal feed, and produce fertilizers used in plants (Ojha *et al.*, 2020; Samimi *et al.*, 2023). The principle of this method is similar to that of composting but consumes less energy, and the production process occurs relatively quickly and has an economic potential of up to 300 percent (%) of the initial investment (Rosenboom *et al.*, 2022). However, this method requires complex treatments during development and cultivation. This technology is generally used in tropical Asian countries, such as Indonesia, Malaysia, and Singapore.

4. Composting is a widely applied engineering method depending on the desired needs of each local government and stakeholder. This method adopts a third hierarchy, namely utilization. Composting is a natural process of converting food waste into high-nutrient compost (Hamid *et al.*, 2019; Palaniveloo *et al.*, 2020). This process involves a mixture of additional

ingredients in the form of dry leaves or straw, which are naturally decomposed by microorganisms. This prospective method to reduce large amounts of food waste is constrained by the time required.

5. The waste-to-energy method transforms food waste into other energy sources, such as electricity or heat, using gasification and pyrolysis processes (Hosseinzadeh *et al.*, 2022). Food waste is converted into gas or oil, which can produce energy, making it less dependent on fossil fuels (Ashokkumar *et al.*, 2022). This is similar to the fourth hierarchy of food waste management, namely, energy recovery, but requires a relatively high initial investment.

6. Anaerobic digestion, similar to the previous method, requires a higher initial investment and has a relatively high potential for environmental impact. This technology converts waste into biogas and digestates via organic digestion in the absence of oxygen (Tawfik *et al.*, 2023; Thompson *et al.*, 2020). This method produces biogas, which is an energy source, whereas the digestate produced is an organic fertilizer with rich nutrients (Baştabak and Koçar, 2020).

7. Integrated food waste management involves various technologies and methods for managing food waste, such as composting, anaerobic digestion, and BSF, until the resulting residue is disposed of in landfills and waste banks (Farahdiba *et al.*, 2023). This approach is placed at the end, even though it has a high potential for recycling because the residues are disposed of in landfills.

8. Internet of Things (IoT) and Artificial Intelligence (AI) technologies can be combined with previous approaches for monitoring, managing, and optimizing various selected food waste management approaches in integrated food waste management (Oruganti *et al.*, 2023; Ukhurebor *et al.*, 2021). Intelligent sensors, real-time data analysis, and data-smart systems help identify patterns, predict market demand, and optimize food waste management operations such that the residues generated are microscopic before disposal into landfills.

Achieving more sustainable food waste management, reducing waste, lessening environmental effects, and maximizing the value of food waste can be accomplished using a combination of technologies and methodologies relevant to local conditions and the scale of food waste management.

Multicriteria decision-making methods

This section summarizes the literature review on the use of the MCDMA method in various food-waste-related and investment-related topics. MCDMA has been implemented to aid problem modeling in selective decision-making processes related to food waste, considering various criteria (Adar Yazar *et al.*, 2023). Several MCDM/A models are applied to the subject of food waste as Elimination Et Choix Traduisant la REalite (ELECTRE), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), Technique of Order Preference by Similarity to Ideal Solution (TOPSIS), and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) which are examples of the analytical hierarchy processes (AHP) (Sadhya *et al.*, 2021). According to Kandakoglu *et al.* (2019), common categories include the single-criterion synthesis method, which outperforms MCDMA. The synthesis method based on a single criterion must consider the incomparability of the alternatives listed below: AHP and TOPSIS (Vassoney *et al.*, 2021). This model combines many perspectives into a single function, which is then optimized. Compensatory rationality also features prominently in this approach; the outcomes of alternative food waste that performs poorly on one criterion can be improved by its performance on other criteria (Bortoluzzi *et al.*, 2021). Non-compensation and outranking approaches are the only ones where a trade-off connection between criteria and indicators occurs (Kravchenko *et al.*, 2020). Outranking approaches within the MCDMA model are tolerant of non-comparable ties between options (Akram *et al.*, 2021). The interaction between these options aids in issue-solving by establishing outranking (and under the preferences of the decision-maker, which are typically initiative and partial) (Yannis *et al.*, 2020). Therefore, the justification for non-compensation can only be provided by focusing on criteria with a clear preference between the two options, irrespective of the relative importance of those criteria (Edjossan-Sossou *et al.*, 2020). In collaboration with MCDMA, fuzzy theory has been applied to obtain the uncertainty and ambiguity often found in food waste from a scientific perspective (Javanmardi *et al.*, 2020). For instance, the outcomes of analysis (synthesis), where obtaining the frequency from fuzzy logic in conjunction with several other techniques, have led to the development of newer, more suited, and adaptable techniques that can impact future trends in sustainable food waste (Masood and Ahmad, 2021). Ukpanyang *et al.* (2022) provided an overview of the MCDMA method based on sustainable food waste generation, including AHP, PROMETHEE, and TOPSIS. The study presented the analysis results for efficiency, cost, environmental impact, reduction strategies, waste management methods, site selection, and location selection for food waste management methods (Hashmi and Alam, 2019; Llopis-Albert *et al.*, 2021). These serve as a reference for stakeholders, decision-makers, and third parties to establish the best compromise for implementation. Meanwhile, different analyses (Liu *et al.*, 2008) from various studies (including integrated and systematic approaches) and decision-making methods require assistance in planning and sustainable programming for food waste (Wu *et al.*, 2021). In this analysis, the authors discussed the importance of assisting collaboration between decision-makers, stakeholders, and third parties for the analyzed problem and suggested the most efficient approach to implementing the MCDMA model (Govindan, 2022). Furthermore, the concept of sustainable food waste applies the Circular Economy (CE) concept based on the problems that occur (Teigiserova *et al.*, 2020). This sustainability research contributes to a review of various factors, technologies, and opportunities to address food waste, resulting in a proposal for problem analysis (Lopes de Sousa Jabbour *et al.*, 2021). Various contributions and collaborations using the MCDMA have addressed global food waste problems. For example, Gardiner (2020) proposed the integration of some Life Cycle Assessment (LCA) methods, Life Cycle Cost (LCC), sustainability, and Social Life Cycle Analysis (SLCA) with approaches such as MCDA and System Dynamics (SD). This study aimed to obtain the most sustainable proposals from a life cycle perspective to analyze the complexity of systems and sustainable tools emerging for analyzing sustainable food waste in various countries (low-income, middle-income, and high-income). This study also advised low-income nations to use the ABM hybrid method while considering technological, economic, social, and environmental perspectives. Engineering is creating and implementing a systematic technique to evaluate sustainable food waste and identify numerous solutions for food waste using the AHP method in diverse developing nations. This analysis showed that increasing the efficiency and effectiveness of food waste is desirable. Simultaneously, methods such as incineration and anaerobic digestion are the least recommended because of their high energy consumption, relatively high pollution, and high initial investment from the developing countries analyzed (Khan and Kabir, 2020). Further research (Khan and Kabir, 2020) developed an assessment model in the form of an Environmental Impact Assessment (EIA) in the process of an environmental impact assessment used in project planning and development, in this case, food waste, by helping to analyze, estimate, and evaluate the environmental impact of food waste management practices, by considering these factors. The study indicated that several countries that are intense in sustainable food waste, such as Germany, the Netherlands, Denmark, South Korea, and Australia, have implemented laws for food waste, management practices, prohibiting food waste disposal in landfills, public awareness campaigns, implementation of programs and initiatives that promote responsible handling, reduction of food waste at the source, and development of management alternatives that are first implemented on a small scale (Pharino, 2021; Shen *et al.*, 2023; Terleeva, 2022). Several studies have implemented MCDMA, stressing the indicators/criteria used in addition to the numerous aspects of each food waste technology and the potential for Key Performance Indicators (KPI) (Bortoluzzi et al., 2021). Papargyropoulou *et al.* (2014) outlined a comprehensive set of policy criteria regarding alternatives to food waste in the book "Sustainable Food Waste Management: A Comprehensive Literature Review on LCA-MCDMA Methodology," examining numerous techniques and solutions employed by the scientific community to evaluate sustainability in food waste using a fusion of LCA and MCDM approaches. This study offers a collection of sustainability indicators for evaluating energy alternatives, food waste assessments, and regulations. According to the literature mentioned above, studies on rating and choosing sustainable food waste do not consider preferences when weighing the trade-offs between different criteria and performance traits (Brenes-Peralta *et al.*, 2020; Romero-Perdomo and González-Curbelo, 2023).

Numerous surveys have also provided performance information for other options based on the findings of various combinations of factor levels and performance qualities. To resolve this issue and select a sustainable food waste solution, an evaluation of the trade-offs between several performance criteria may be necessary (Muscat *et al.*, 2021). The literature review revealed that NVivo and Vos Viewer bibliometric analyses using performance criteria and MCDMA decision-making methodologies were used to prepare this study (Bortoluzzi *et al.*, 2021). The importance of this study lies in its determination of the differences between economic, social, policy, technological, and environmental indicators and the criteria used in the decision-making process for evaluating and selecting sustainable food waste management strategies from an MCDMA perspective.

Assessment Criteria for food waste sustainability alternatives

The literature contains several sample studies on the application of the MCDMA approach to assessing sustainable food waste alternatives (Allesch and Brunner, 2014). However, it is challenging to identify and select factors that allow for the selection of sustainable options. The decision maker must expend significant cognitive effort because quantitative and qualitative data, as well as more nuanced data pertinent to each criterion, will determine the optimal number of criteria to be used. This article is used in this study. Performance indicators and assessment criteria are discussed in this study because they are intended to evaluate and compare various solutions across alternative technologies. Depending on the production sector, KPI may incorporate subjective or objective indicators. It is important to know which MCDMA method is being utilized and which performance indicator is best for a decision strategy to evaluate sustainable food waste technology. The combination includes several MCDMA modes, including the grey relational analysis (GRA) approach and other techniques, including AHP, fuzzy methods, or a mixture of various techniques (Banaeian *et al.*, 2018). Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis is a matrix that uses the PROMETHEE approach (Indrajayanthan *et al.*, 2022) and suggests combining Monte Carlo simulation and PROMETHEE (Mavrotas and Makryvelios, 2021). Therefore, managers of private enterprises that create sustainable goods from food waste may have different needs when evaluating sustainable food waste technology than those in the public sector (Lohri *et al.*, 2014). Managers' reasons for systematic business planning in selecting various technologies can be supported by identifying the most commonly applied factors through the MCDMA model. In addition to food waste research, Martin-Rios *et al.* (2020) advised that the following qualities should be present in management: a) clarity that technicians, researchers, and other stakeholders can understand; b) simplicity and uniform definition to prevent overuse and misinterpretation of technical outcomes; and c) relevance for the chosen parameters to satisfy operations' and stakeholders' needs. Several studies can provide insight into the complexity of the systematization of indicators and criteria when observing issues that arise in a sustainable context. Vittuari *et al.* (2016) found that resource efficiency, food waste reduction, environmental impact, socioeconomic impact, economic sustainability, and regulatory compliance are the six general criteria for sustainable food waste. However, in this series, the authors discussed how the dimensions of sustainability categorize these six criteria. A similar approach identified five criteria but did not involve indicators representing the social dimension of sustainability. Furthermore, Yeung *et al.* (2020) used indicators and criteria consistent with the United Nations, such as the agenda for 2030, but needed to consider environmental factors. Therefore, it is not appealing to utilize these indicators and criteria. In contrast (Reisch *et al.*, 2013) described eight criteria involved with social and economic dimensions and the environment but did not involve the policy domain. Furthermore, several other studies have not considered the technical or policy dimensions of these alternatives. Utilizing additional tools to supplement the indicator portfolio and conducting a thorough sustainability assessment following the three dimensions of sustainability (economic, social, and environmental) to generate ten analysis criteria is another illustration of how the choice of indicators can vary. The authors' method, one of the most popular instruments for environmental evaluation, was LCA. The challenge in choosing indicators was to reduce sustainability concerns and concentrate on energy efficiency. The literature advises managers to select the most effective renewable energy by establishing indications and criteria to help them make decisions. Three review papers published over the past year (2015–2017) were identified from five indexed, highly regarded journals. Most of the studies the authors reviewed focused on environmentally friendly food waste. Twenty-five criteria were identified for analysis. This study aimed to show that decision-making and the issue of sustainable food waste may coexist. Finally, several settings may be involved in indication selection; therefore, these need to be studied first. This study outlines different standards that can be applied to address pressing problems and reduce food waste in various nations (low-, middle-, and high-income). The most popular or pertinent indicator for measuring sustainable food waste was mentioned in this analysis (Iyamu *et al.*, 2020). Consequently, the choice of criteria used to evaluate various options generally affects the results of the MCDMA method. Weights were applied to the performance of each criterion/indicator based on the selection, sorting, and classification of sustainable alternatives to food waste. This study's methodology aimed to enable future scholars to reproduce this research in other domains using bibliometric analysis. The aim of the current study is expected to fulfill sustainable solutions at Diponegoro University, and this study was conducted in 2023.

MATERIALS AND METHODS

This study used a bibliometric approach to effectively select and evaluate food waste technologies. Conducting a bibliometric analysis in the context of sustainable food waste management and multi-criteria decision-making is essential because it provides a data-driven overview of research trends, key contributors, and voids in the field. The first benefit of bibliometric analysis is that it offers a broad perspective on the research environment and traces knowledge development over time. This analysis highlights the expanding significance of sustainable food waste management and multi-criteria decision-making among academic and practitioner communities by quantitatively evaluating publication trends, authorship patterns, and collaboration networks. The analysis then assists in identifying gaps and regions in which the research is under-examined. This understanding is essential to focus on current research initiatives and funding in areas with the potential to make significant contributions. For instance, the analysis might highlight particular aspects of sustainable food waste management that have received less attention, such as social equality issues or technological integration, leading researchers and policymakers to concentrate on bridging these knowledge gaps. To ensure that the results of this study may be used as a reference in other areas of research addressing sustainable food waste or even to update the findings on future perceptions, a systematic review of the literature was conducted based on existing reviews identified in the literature (Redlingshöfer *et al.*, 2020). The procedure described by Kumah *et al.* (2019) in the literature review is as follows:

- Step 1: Identification of opportunities in the research conducted
- Step 2: Establishing the criteria for selection and the database for the paper selection
- Step 3: Establishing categories for the quantitative examination of scientific output from the chosen field of research
- Step 4: Identifying the pattern of ongoing research and study opportunities for future perceptions through bibliometric analysis using VOSViewer and NVivo.

The importance of sustainable food waste technologies was stressed in the introduction of this study, which served as a justification for the first phase involving identifying potential research opportunities (Cicculo *et al.*, 2021). Examining the most frequently cited passages from diverse scientific studies, the technical application of bibliometric analysis in this study crucially established standards and optimization techniques in sustainable food waste research (Roslan *et al.*, 2022; Zhou *et al.*, 2022). The second step was the selection of the literature and databases. At this stage, the selection was performed. Thus, the databases used for literature adoption were Scopus and Science Direct because they have large publishers and diverse collections of literature on sustainable food waste. The database was utilized for current systematic reviews and bibliometric publications. After selecting a database, keywords in the examined themes were identified to reduce the selection of particular literature. Therefore, the keywords used to answer the objectives of this study were food waste, multicriteria decision-making analysis, food waste technologies, food waste economy, and sustainable development. Keyword determination was the purpose of this study.

● Group 1: Accomplish the idea of food waste and its variations from numerous articles using the keyword "food waste."

● Group 2: Food waste technologies to establish the aims of papers focused on various technologies and substitutes for food waste.

● Group 3: Food waste economy to filter publications on the conversion of food waste into economic advantages.

● Group 4: Sustainable development to filter out differences and the idea of sustainability

● Group 5: Multi-criteria decision-making aid: restrict literature searches using any field of the study's MCDMA methodology.

After the initial step of keyword selection, the "AND" operator is used to split up keyword group combinations, while the "OR" operator is used to split up cooperation words within the same group. Table 1 outlines the keywords and the preferences that justified their choice.

In addition to keywords, other filters allow for selectivity in literature selection. First, only literature written in English was selected because it is a common language used in bibliometric research. In addition, this language ensures that it will have the largest readership and the highest number of citations, thereby creating opportunities for research collaboration that can be identified using bibliometric methods. Options were also limited to a literature search of conference proceedings, reviews, and early access to the Science Direct and Scopus databases, with a publication deadline for each year (time-lapse:2014–2023). The search parameters (titles, keywords, summaries, and abstracts) provided 500 literature items compiled in the Endnote reference program. A sample of 146 literary works provided statistical research methods that could support the agenda on this issue. The classification used in Step 3 to retrieve data from each cited article is described below. The following categories were created using research from 146 articles: sustainable food waste, an analysis of food waste, used performance standards for analyzing food waste, using the MCDMA technique to examine sustainable food waste, authors and collaborators on literary works, authors' and co-authors' countries, publisher's journal, publication year, and the total number of citations for each piece of literature. Apart from these categories, other data were grouped to more clearly identify advanced sustainable food waste alternatives and optimization methods. Therefore, categories were established to enhance the thematic analysis, including the most prolific author over time, the most significant journals for study, and the nations with the most noteworthy number of publications, partnerships, and citations. Step 4 involved data analysis and study opportunities in the research subjects from 146 pieces of literature chosen once the data collection categories had been determined. VOSViewer and NVivo software were used to gather and analyze the chosen sample data. The VOSViewer can produce maps and enable group viewing of the subject under study using the nodes it represents. The map developed in this study depicted the authors' keyword network and how frequently it appeared over time. Additionally, "Word Clouds" were developed utilizing NVivo software to extract quantitative data from particular literary works to define word clouds about sustainable (economic, environmental, and social), political and technological criteria, and current MCDMA. Word clouds represent the KPI and are the most popular model criteria. The 146 chosen papers were summarized using the word cloud because review papers on sustainable food waste were associated with numerous KPI and MCDMA models. The research methodologies used in Step 4 differed from those used in prior review papers, allowing for fresh analytical viewpoints. A word cloud was used to select the primary criterion or KPI models and multi-criteria to enhance the bibliometric analysis, and 146 publications were chosen randomly. Sustainable technologies to reduce

Table 1: Outline keyword preferences

Group	Keyword
Group 1	Food Waste OR Food waste OR Food Waste behavior
Group 2	Food Waste Technologies OR Food Waste Management OR Food Waste Alternative
Group 3	Food Waste Economy OR Food Waste Economy to Economy value
Group 4	Environmentally-friendly OR Environmentally-friendly OR Efficient OR Efficient OR Cleaner
Group 5	Multicriteria decision OR Food waste multicriteria OR Multicriteria evaluation OR Multi objective analysis OR Multi objective decision OR Multicriteria decision

food waste have also been considered. Consequently, cluster analysis (k-means) and dendrogram generation were performed. When evaluating sustainable food waste technologies against KPIs or MCDMA models, this analytical visualization was performed to simplify the presentation of the results and make it possible to observe patterns. The groups into which this information was collected and analyzed are depicted schematically in Fig. 1. Notably, data related to the suggested categories were gathered for each target in the literature. These data enabled a cross-analysis between the MCDMA approach and the performance criteria for sustainable food waste decision-making.

Quantitative bibliometric examination of the knowledge database

The findings of the bibliometric analysis of the 146 selected papers are presented in this section. Descriptive and inferential statistics are presented in this section.

Typical bibliometric findings

The initial analysis referred to the annual growth rate of the sample in terms of publications (literature). The annual growth rate was expected to reach 14.95% between 2014 and 2023. From 2017 onward, the number of items included in the analysis increased significantly. For five years, the 2019–2023 sample increased from 10 to 24 studies, an increase of 15.5%. These findings suggest that researchers in mathematical models based on MCDMA methodologies are beginning to capture the attention of decision-makers regarding which technology to use. The annual growth rates of publications between 2014 and 2023 are shown in Fig. 2.

Fig. 3 shows the ten journals with the most articles published on the research topic after an increase in annual publishing was noted.

The journal with the most published articles was "Sustainability (Switzerland)," and the study sample comprised 32 articles from this publication. This journal has a considerable quantity of published material compared with no more than 20 other journals. Only five and three articles, respectively, from the "Waste Management and Research" and "Waste Management" journals were used in this study. Based on these findings, journals can be viewed as viable alternatives to distributing studies on decision-making using a multi-criteria approach and sustainable food waste to enhance the number of article readers. Additionally, it is useful to ascertain the number of papers and literature most frequently cited by the journals that publish this study. Table 2 of the ten papers in the investigated database with the most citations reveals that the first three papers received 300 or more citations.

Notably, the most frequently cited papers published in "Sustainability (Switzerland)" journals did not reflect the visibility offered to publish papers due to conditions during the year of publication where the publication theme of "pandemic, COVID-19" was one of the problem factors that were appropriate to the

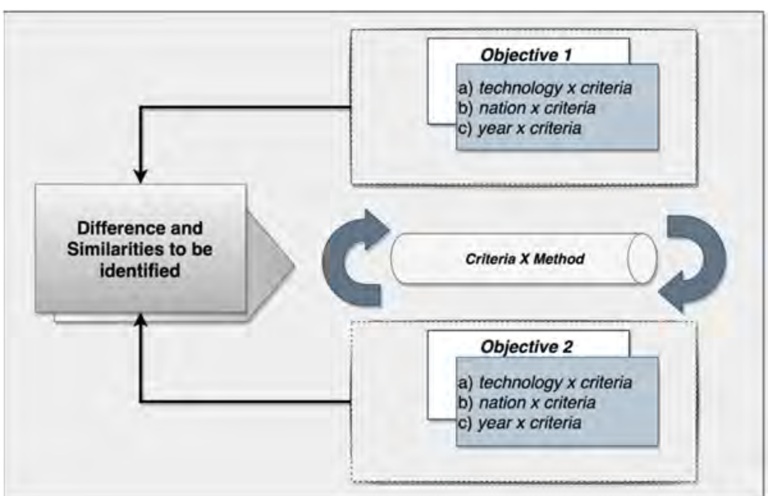

Fig. 1: Schematics representation of bibliometric analysis

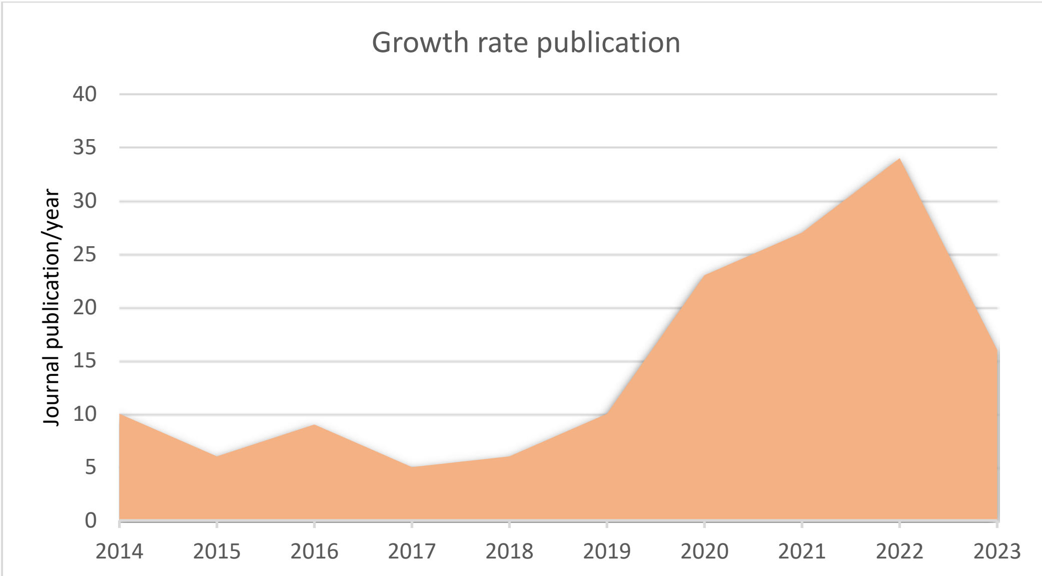

Fig. 2: The rate of publishing growth per year from 2014 to 2023

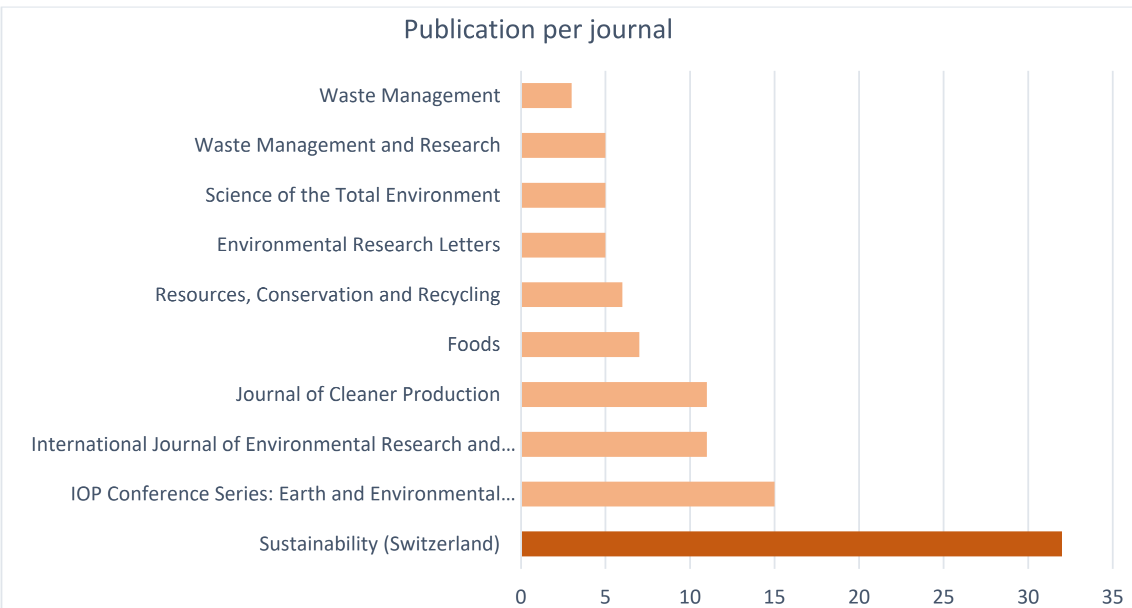

Fig. 3: Number of Publication per Journal

topic of food waste generation. This invisibility may indicate that the literature aims to identify knowledge patterns and has become a valuable reference for past and future perceptions of sustainable food waste and decision models using a multi-criteria approach. From the previous analysis, it was possible to identify the most frequently published authors on food waste. Fig. 4 shows the authors with the most published studies in the reviewed literature. One author had two publications. The author was Wong

Table 2: Most cited publication in literature for this study

Title of publication	Journal Where It Submitted	Number of citations	Sources
Challenges, opportunities, and innovations for effective solid waste management during and post-COVID-19 pandemic	Resources, Conversation and Recycling	346	Sharma *et al.,* 2020
Challenges and Practices on waste management and Disposal during the COVID-19 Pandemic	Journal of Environmental Management	135	Hantoko *et al.,* 2021
Redesigning a food supply chain for environmental sustainability – An analysis of resource use and recovery	Journal of Cleaner Production	113	Krishnan *et al.,* 2020
Data-driven optimal dynamic pricing strategy for reducing perishable food waste at retailers.	Journal of Cleaner Production	100	Kayikci *et al.,* 2020
Sustainable food systems—a health perspective	Sustainability Switzerland	84	Lindgren *et al.,* 2018
Food loss and waste in food supply chains. A systematic literature review and Framework development approach	Journal of Cleaner Production	80	Chauhan *et al.,* 2021
Performance evaluation of reverse logistics in food supply chains in a circular economy using system dynamics	Business Strategy and the Environment	56	Kazancoglu *et al.,* 2021
Repercussions of the COVID-19 Pandemic on solid waste generation and management strategies	Frontiers of Environmental Science & Engineering	54	Liang *et al.,* 2021
COVID-19 and waste production in households: A trend analysis	Science of Total Environment	53	Leal Filho *et al.,* 2021
A senior manager's perspective on food waste management in Shanghai full-service restaurants	Journal of Cleaner Production	50	Filimonau *et al.,* 2020

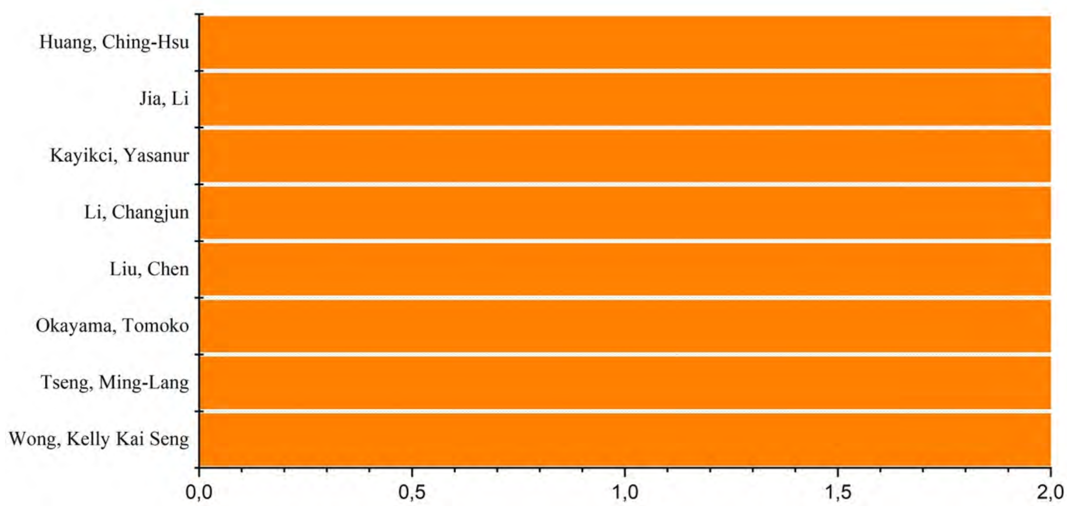

Fig. 4: Authors with the most published studies in the sample

Kelly Kai Seng from Rahman University College, Kuala Lumpur, who describes alternatives and habits to food waste that arises. Other prominent writers during the period analyzed were Li Changjhun (Department of Environmental Science & Engineering, Fudan University), Tseng Minglang (Institute of Innovation and Circular Economy, Asia University), Okayama Tomoko (Faculty of Regional Development, Taisho University, Tokyo), Jia Li (College of Economics and Management, Inner Mongolia Agricultural University), Liu Chen (Sustainable et al. Area, Institute for Global Environmental Strategies), Kayikci Yasanur (Department of Engineering and Mathematics, Sheffield Hallam University), and Huang Ching-Hsu (

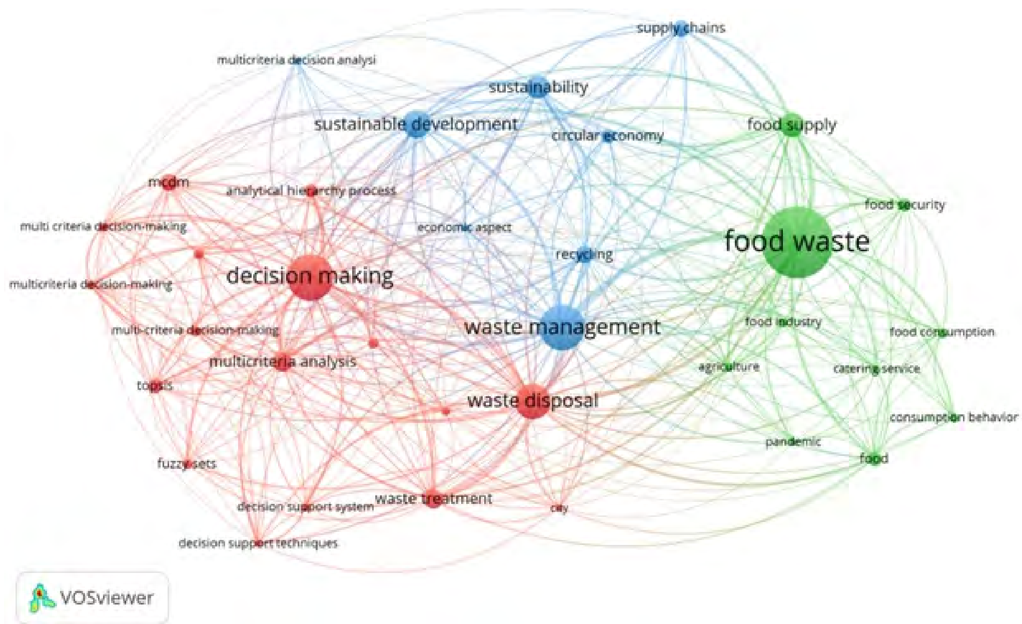

Fig. 5: Author's network keywords

Department of Hotel and Restaurant Management, National Pingtung University of Science and Technology), all of whom discuss different perspectives on sustainable food waste from different fields of study.

Ascertaining whether there is a pattern in the authors' usage of keywords is crucial when selecting reference studies to apply the multi-criteria method to food waste scenarios. Considering that each keyword in the network has at least two citations, Fig. 5 from VOSViewer shows the distribution of keywords in the network for the three groups.

The picture shows the words "Decision making'' and "Food Waste" as highlights. The word "Decision making" refers to various ways of quoting the term "multi-criteria decision making" or "MCDMA," which is simplified in this study by its acronym. Most terms in the other groupings were connected to these two words. As a result, it is feasible to confirm the author's propensity to utilize "food waste" and "decision making" to summarize their research. Confirming that the term "fuzzy" appears in various clusters is also possible. Along with other concepts and multi-criteria models, fuzzy techniques have been used to address FW, technology, and sustainability concerns. Therefore, "fuzzy sets," "fuzzy logic," "fuzzy topsis," and "intuitive fuzzy sets" are all visible. Analyzing similar word networks over time also hints at how authors might cite their studies. Fig. 6 shows that starting in 2019–2022, the keywords highlighted in the image show the frequency of use as well as possibly suggest that research will be made more visible on databases such as Scopus and ScienceDirect.

Fig. 7 shows the number of publications by country for the researchers' countries of origin. China, Turkey, and Greece published the most research papers relative to their home nations.

Word clouds

Additional bibliometric sources were chosen to fulfill the goals of this study, which include identifying the current state-of-the-art in food waste and making decisions using a multicriteria approach. As a result, a 7-word cloud was created to demonstrate the KPI in several sustainability dimensions and multicriteria decision-making models (Fig. 8a to 8g). A multicriteria approach's word cloud is shown in Fig. 8a. The managers' responses served as the primary and general data sources for this model. Other models, such as "DEA" or "PROMETHEE," are less noticeable, suggesting that fewer researchers used them in the sample.

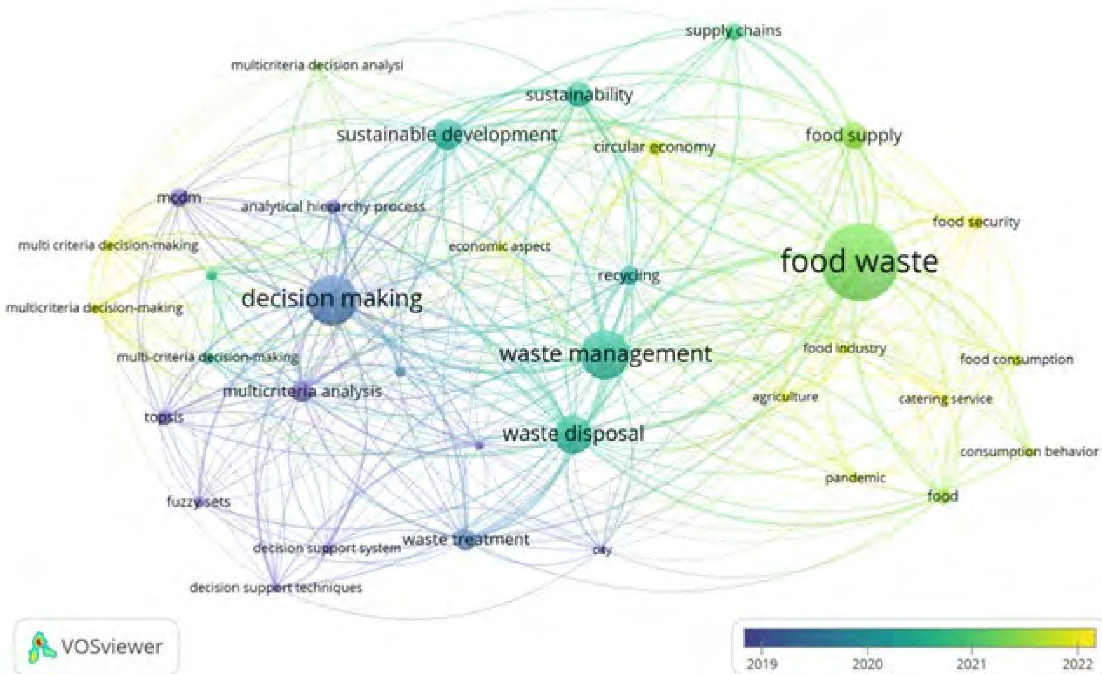

Fig. 6: Network of keywords analyzed over time

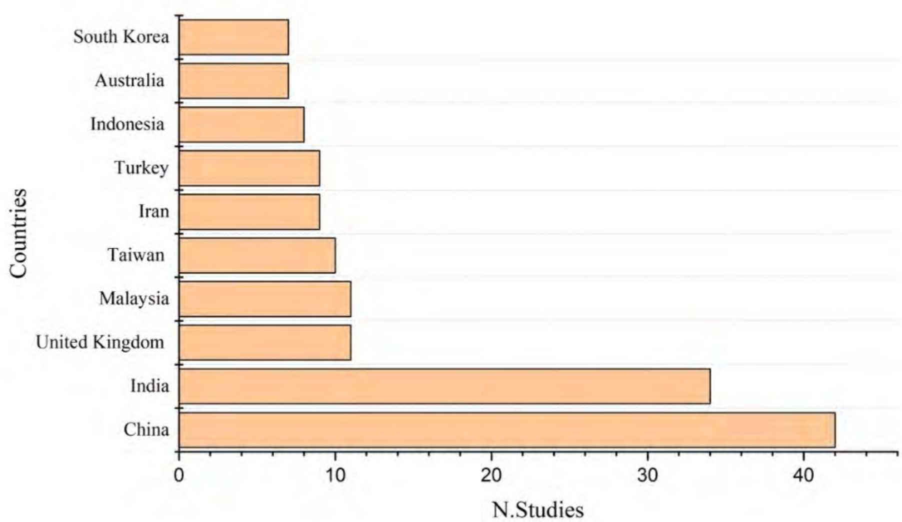

Fig. 7: Number Publication Base on Country

The KPI has a collection of word clouds to categorize the preference trends of each researcher for sustainable food waste. Fig. 8b shows a word cloud involving various sectors of food waste, sources, and factors for adopting "sustainability." The word cloud shows that the most important words are "food, waste, " and " management." However, some findings indicate that each writer must use phrases that come to mind to obtain sustainable food waste regardless of the technology or circumstances under consideration.

Fig. 8: Multi-criteria models and their most common indicators as a word cloud

The results of the world cloud show that the words "food, waste, and management" are fascinating to analyze the world cloud from each different sector and understand its relevance. Fig. 8c shows the word cloud exclusively in terms of economics. It is possible for an analysis of the word "economy" to be a relatively important factor in applying the concept of sustainable food waste. However, there are also words in the form of "renewable," "business," and "bio-economy," which are relatively essential to observe but are still little analyzed in the economic sector. The phrases "technologies" and "optimization," which are connected to costs for evaluating the performance of sustainable technologies and are frequently incorporated into essential elements of the economic sector, are also present in addition to these words. Therefore, sustainable food waste has a propensity to represent the economic sector. Fig. 8d displays the word cloud from the environmental sector that was employed in the research's chosen literature, as opposed to the economic sector, which displays the phrases "impact," "global," "CO," and "emission." These findings demonstrate that each researcher attempted to study multiple options for each case and condition. The multi-criteria model simultaneously examined indicators and several alternative food waste methods. Another finding from this study is that nations have attempted to consider several indicators directly connected to the emissions produced in the context of climate change. In the social sector analysis presented in Fig. 8e, opportunities exist for stakeholders represented by the words "business," "product," "reducing," "marketing," and "innovation." This phrase demonstrates the significant involvement of the social sector in various positive social impact issues, including higher income, the desire to lessen the sector's influence, and numerous other repercussions. Consequently, significant problems persist in the social, environmental, and economic sectors. Global and national policy issues are crucial in assessing sustainable food waste. The word cloud of the decision-maker-related policy issues is shown in Fig. 8f. The phrases "public," "regulation," and "society" are conspicuous in the image as evidence.

These phrases imply that the important deciding factors for sustainable food waste are financial incentives and clear explanations of public policies. Policy concerns ultimately impact other sectors (economic, environmental, and social) because they are not entirely solved. Finally, as a sector analyzed with the subject of sustainable food waste, it can be used as a consideration for decision-making. Fig. 8g shows the words related to technical issues. This word cloud shows the words “costs,” “valuable,” “strategy,” and “mitigation,” which are relatively highly adopted. These words represent important indicators for decision-making regarding sustainable food waste. Thus, a strategy is needed to support sustainable food waste with a lower environmental impact and relatively lower investment and maintenance costs, as well as to obtain valuable products from the application of various technologies.

Bibliometric analysis result of inferential statistic

This section summarizes the findings of the analysis based on clusters connected to the principles of sustainable food waste, performance standards, and decision models using a multi-criteria approach following the objectives of the study. The next section describes the framework of multi-criteria decision-making; a methodical and deliberate procedure was used to assign matrix values for environmental, economic, social, and ethical criteria. Greenhouse gas emissions, land use, technological efficiency, technological maturity, technological capacity, energy efficiency, and land impact are only a few environmental criteria recognized alongside quantifiable units and scales. The environmental impact of the alternatives was measured using these criteria. Similar to technical criteria, economic criteria are monetary in nature and include maintenance costs, investment costs, and payback, which are scored to reflect their relative magnitudes among options. Scores that capture the social implications of each option are generated by defining and evaluating social issues using quantifiable units such as social acceptability and policy approval. Although qualitative, ethical standards are nonetheless crucial, necessitating the formulation of pertinent ethical considerations, qualitative scales, and the assignment of scores that correspond with the ethical alignment of options. These ratings are stored in matrices with rows representing options and columns representing criteria. Collectively, these matrices offer a structured basis for the following multi-criteria aggregation procedures, allowing for a thorough evaluation process that assists decision-makers in choosing sustainable food waste management options consistent with a wide range of criteria.

Sustainable food waste technologies

The results of the first analysis presented various sustainable food waste technologies that were studied in the 146 papers selected for this study sample from 2014 to 2023. Fig. 9 shows a dendrogram for sustainable food waste technology from the KPI analysis used in various studies. Categorizing these three groups is possible. These three groups were selected for in-depth analysis of how each technology group was selected for the selected studies.

Sustainable waste-reduction techniques cover a wide range of approaches to reduce waste and increase resource efficiency, which is why they are important in the development of circular economic ideas. By encouraging longer product lifespans, less packaging, and more conscientious purchasing decisions, source reduction and prevention programs can reduce waste initially. Instead of entering landfills, biodegradable materials can be recycled into nutrient-rich compost via composting, anaerobic digestion, biosolid landfill diversion, and organic waste management. By repurposing waste products through recycling and material recovery procedures using cutting-edge technologies, reliance on virgin materials can be reduced. The dual benefits of trash reduction and clean energy generation are realized through the use of waste-to-energy and biomass conversion technologies that focus on converting nonrecyclable garbage into renewable energy sources. Efforts to reduce trash can be bolstered using cutting-edge technology and methods such as smart waste management systems and sensor-based sorting. Choosing sustainable food waste management strategies requires a commitment to a set of guiding values that include respect for the natural world, economical use of resources, and active participation in the local community. One general principle is to follow a waste management hierarchy, with waste avoidance at the source (via better planning, purchasing, and consumption habits) given the highest priority. The first step in developing efficient food waste management is to

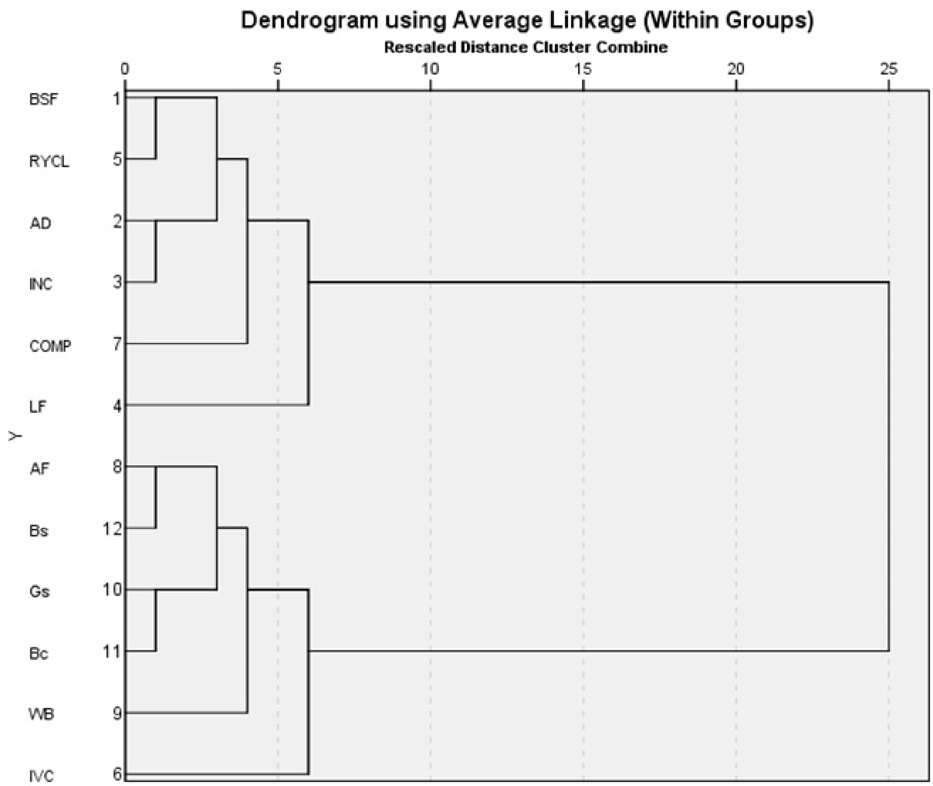

Fig. 9: Sustainable food waste technologies hierarchical cluster from KPI analysis

implement a system for source separation in which waste is separated at the point of production. In conforming to the intent of sustainability, methods that minimize the impact on the environment should be used, such as composting, BSF, waste banks, recycling, and anaerobic digestion of organic waste. The framework provided by municipal legislation and policies for waste management techniques must be carefully navigated. Fostering a culture of waste reduction and responsible consumption requires the active participation of communities and stakeholders through awareness programs. Smart bins and garbage-tracking applications are two examples of cutting-edge technologies that can be implemented to improve efficiency and collect useful data for better decision-making. The findings of this study demonstrate the value of applying economic principles to the problem of food waste by providing an enticing framework that prioritizes waste reduction, allocating resources efficiently, and encouraging effective practices at every stage of the food supply chain. Economic analysis highlights the need to minimize food waste and increase its value by evaluating the monetary costs of food production, distribution, and disposal. Businesses, households, and other stakeholders are pushed to adopt waste reduction measures in response to financial incentives that reward thrifty behavior and require them to tighten their inventory controls, reduce their portion sizes, and improve their distribution processes. Furthermore, economic principles stress the significance of resource efficiency, elaborating on how reducing food waste reduces the wasteful use of resources such as water, electricity, and agricultural inputs. This improves sustainability and solves critical problems caused by limited supplies. The KPI results show various types of food waste technologies. Table 3 presents the behavior of each cluster in several studies that employed these markers. For instance, using the indicators “GWP,” “Land use,” “Investment Cost,” and “Payback” demonstrated that the first cluster was partially displayed. The cluster analysis results

Table 3: Citied studies' cluster behavior

Final cluster centers			
Impact analysis	Cluster		
	1	2	3
GWP	11,4	30,21	32,02
Land use	10,60	30,12	28,01
Environmental impact	5,30	34,01	28,04
Social acceptance	21,50	28,01	9,04
Investment cost	11,72	32,12	28,04
Maintenance cost	10,05	25,12	25,42
Payback	25,01	9,02	32,04
Tech efficient	28,50	25,04	34,02
Tech maturity	18,79	30,02	27,02
Tech capacity	19,96	32,34	19,02
Energy efficient	20,78	5,34	8,04
Policy acceptance	8,45	1,23	0,02

showed that the average research assesses "Animal feed" and "Waste bank," "Composting," "BSF," and "Recycle" using the same indicator. This pattern increases the possibility that these technologies may use similar signs in an evaluation study conducted prior to decision-making.

The second cluster was significantly different from the first cluster. Indicators such as "GWP," "Land Use," and "Investment Cost" are more widely used in the average study. This fact may indicate that the terms used are "environmental impact," "tech capacity," and "And maintenance cost," indicating that the technology in the form of "landfilling, Incineration, and Anaerobic Digestion" does not include indicators of sustainable choice in the context of sustainable food waste from managers who want sustainable technology for food waste. The second cluster was significantly different from the first cluster. Indicators such as "GWP," "Land Use," and "Investment Cost" are more widely used in the average study. This fact may indicate that the terms used are "environmental impact," "tech capacity," and "maintenance cost," indicating that the technology in the form of "landfilling, Incineration, and Anaerobic Digestion" does not include indicators of sustainable choice in the context of sustainable food waste from managers who want sustainable technology for food waste. Therefore, according to the frequency of use of indicators from 146 selected studies, managers may possibly prefer "Land Use," "investment cost," "payback," "environmental impact," and "social acceptance" as indicators that assess sustainable alternative technologies of food waste regarding which to implement. Including other technologies that exist outside of this study, implementation is not necessarily an indicator that is expected to be considered by decision-makers for wider implementation and expansion, and this depends on the existing conditions of each region and their needs.

Evaluating performance against multi-criteria decision models

Performance indicators and MCDMA models, the two primary concepts examined in this research, are combined in this part for analysis. The dendrogram for the cluster analysis is shown in Fig. 10. Three clusters of results are identified.

Performance indicators that share the same multi-criteria may be determined using non-hierarchical cluster analysis. According to the findings, cluster no. 1 includes the indicators "GWP" and "Investment cost," as well as the indicator "Social Acceptance." Cluster no. 2 contains the indicators "Land requirements," "Job creation," and "Technology returns and capacity," whereas cluster no. 3 has all other indicators. Table 4 shows the distribution of performance metrics among clusters using the MCDMA model for selected publications.

Table 5 presents the clusters created by the MCDMA models employed in the cited papers. Using the "AHP" and "Fuzzy" models, the cluster indicators "Social Acceptance," "CO2Eq Emissions," and "Investment Costs" are more pronounced. This finding indicates that the MCDMA models "AHP" and "Fuzzy" are the most practical tools for examining

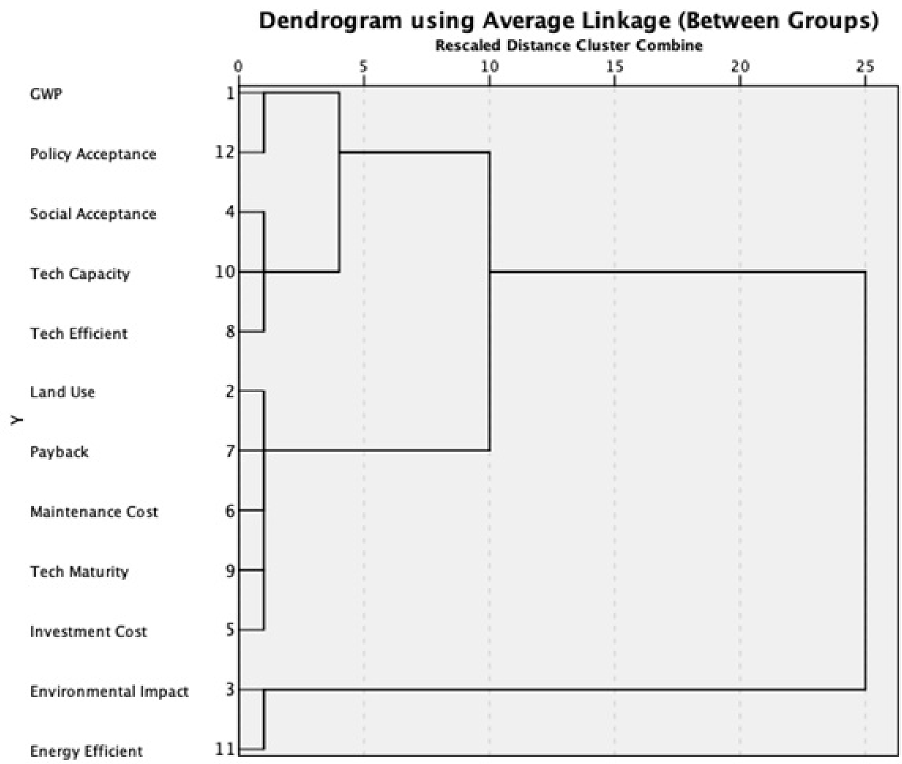

Fig. 10: Performance indicators and multi-criteria models in a hierarchical cluster

Table 4: Combining performance metrics from similar multi-criteria models

Cluster pool		
Cluster	KPI	Number of cases
1	GWP	20
1	Land use	12
1	Environmental impact	25
2	Social acceptance	15
2	Investment cost	10
2	Maintenance cost	10
2	Payback	12
3	Tech efficient	17
3	Tech maturity	10
3	Tech capacity	15
3	Energy efficient	25
3	Policy aAcceptance	20

sustainable types, which are, in this case, represented by the indicators mentioned above. Additionally, the “AHP” and “Fuzzy” methods are frequently used for cluster no. 2 (“Land Requirement,” “Job Creation,” “Return on Capital,” and “Technological Capacity”), but this model is already more similar, indicating the potential for combining the two or the use of more objective indicators in other types of models. In the MCDMA system, Cluster no. 3 had the lowest indicator frequency. This cluster employed the “GREY” model, which was not noted in the earlier clusters, even if “AHP” and “Fuzzy” were still dominant.

Table 5: Cluster center formed from the multicriteria models

Final cluster centers			
Multi criteria method	Cluster		
	1	2	3
AHP	10,98	6,67	2,83
FUZZY	6,78	4,65	1,50
VIKOR	0,74	0,01	0,01
TOPSIS	2,01	0,75	0,15
ELECTRE	1,56	0,45	0,02
WEIGHTED	1,01	0,50	0,15
GREY	0,87	0,00	0,24

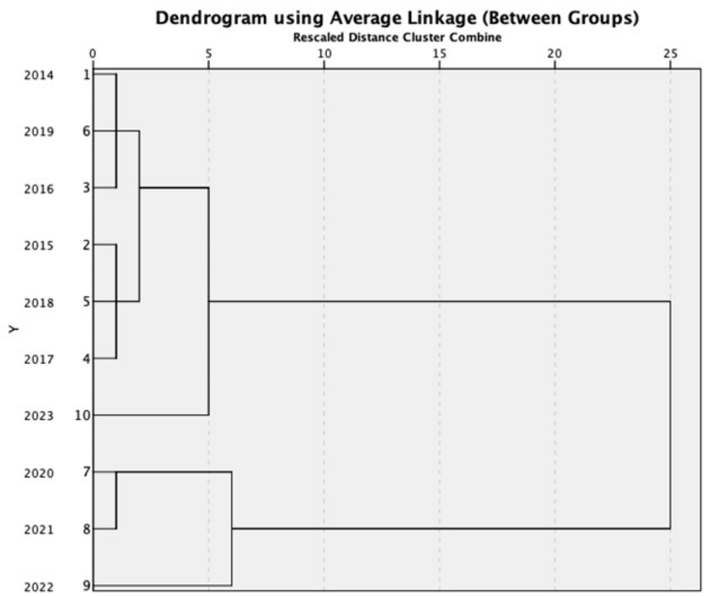

Fig. 11: Hierarchical cluster: annual publication of papers

Annual variation of publications

The annual publication rate of articles was the subject of the final analysis. Thus, based on the performance metrics and multi-criteria models, cluster analysis and graphical depiction of the year of publication were performed. As a result, the initial study focused on the development of a publishing year cluster in relation to performance measures. A hierarchical dendrogram of the annual sample article publication rate is shown in Fig. 11 as a cluster analysis.

The two clusters covered the period 2014 to 2018 and 2019 to 2023. From the cluster center, Table 6 describes the two formed clusters. The first and second clusters had the same annual frequency. The first cluster had work indicators that most often worked in the form of "Land Requirement," "GWP," and "Investment Cost."

Between 2019 and 2023, the performance metrics in the second cluster that were most frequently utilized by the papers presented were "GWP," "Investment costs," and "Operational and Maintenance Costs." The outcomes of this cluster demonstrated how the indicators changed in studies released between 2014 and 2023. As the first and second clusters evolved, linked performance measures, such as the economic and emission pillars, were confirmed; however, the model's policy gradually changed. This results from a policy that has occasionally been applied to the environment and was implemented

Table 6: Using annual indicators and publications, a cluster center was created

Final cluster center		
Impact analysis	Cluster	
	1	2
GWP	2,65	7,53
Land Use	3,52	5,32
Environmental Impact	5,32	5,32
Social Acceptance	0,46	6,75
Investment Cost	1,46	8,00
Maintenance Cost	1,46	7,02
Payback	3,52	7,50
Tech Efficient	0,54	4,02
Tech Maturity	0,79	3,00
Tech Capacity	0,36	6,02
Energy Efficient	0,63	7,79
Policy Acceptance	1,64	2,64

in the 2015 Paris Agreement. As a result, decision-makers are less reluctant to embrace renewable energy sources and pursue specific environmental sustainability objectives. The outcomes of this cluster demonstrated how the indicators changed over time in studies published between 2014 and 2023. When comparing the evolution of clusters 1 and 2, what has been confirmed by economic and emission performance indicators can be observed; however, policy criteria are gradually being excluded from the model. The 2015 Paris Agreement led to the evolution of environmental regulations. This can be explained by the following: Managers should use renewable energy more frequently and set specific goals to reduce climate change. The results included 146 studies selected for bibliometric analysis, allowing for disaggregation by year of publication. These yields are presented, along with the year-in-10-year publication rate and the journal with the most published literature on sustainable food waste. Each study chose one of these as the focus. According to an analysis of publications from 2014 to 2023, there is a noticeable increase in the number of papers presenting the MCDMA approach to the issue of sustainable food waste technology. Compared with previous years, there was an increase in the number of publications between 2019 and 2022. This increase can be explained by increasing awareness of the environmental and sustainability aspects of food waste. This allows researchers to explore useful information supported by an approach that involves a decision-making process using MCDMA. The quantity of materials written between 2019 and 2021 is crucial because it demonstrates how the MCDMA strategy incorporated several sustainable technology facets. This can be attributed to the use of techniques for a more deliberate decision-making process. Recently, this strategy has attracted considerable interest from researchers. The demand for sustainable technology in food waste is the cause of a notable surge (Pardini *et al.*, 2019). Consequently, public policy requirements to support the environmental sustainability of the food waste sector have also been developed, which have prompted initiatives to improve technology efficiency as part of a plan to decrease greenhouse gas emissions and other potential effects on nations worldwide (Prosperi *et al.*, 2020). Despite the limitations of this study, it is feasible to identify established trends for indicators/criteria and the MCDMA model used to choose and evaluate sustainable food waste methods. Accordingly, the following recommendations are proposed:

Proposition 1

Policy indicators should be utilized less frequently than in studies employing MCDMA techniques, such as AHP and TOPSIS, with indicators relating to GWP, economic, and technical criteria.

First, sustainability was applied based on the Triple Bottom Line, which integrates financial, social, and ecological factors (Bachmann *et al.*, 2022; Rejeb *et al.*, 2021). This interpretation of sustainability adds to political, moral, legal, scientific, and cultural dimensions. The context of sustainable food waste was assessed in this study, and five variables were highlighted: economic, technological, political, social, and environmental (Hoang and Nguyen, 2021). To choose and assess sustainable food waste, it is crucial to consider these five factors while studying sustainability. The findings of this study are pertinent because they categorize the variables for which environmental, social, and economic indicators have been identified. The defined performance indicators and assessment criteria are handled equally based on all the indicators examined because they are intended to evaluate and compare various solutions utilizing various technologies. Depending on the KPI, subjective and objective indicators can be used. Therefore, it is important to distinguish which MCDMA method is employed and which performance indicators are most suitable for the decision strategy to evaluate sustainable food waste systems. The parameters for maintenance expenses ($/kWh), payback (year), and investment costs ($) were established to obtain revenue and reduce expenditure based on the economic issues examined. Research on food waste plays a crucial role in the adoption of sustainable food waste in terms of investments and purchasing choices (Johnston *et al.*, 2020). As a result, decision-makers should pay close attention to and consider the indicated criteria. Depending on the MCMDA approach, managers' judgments and tradeoffs between objectives and criteria are considered. Regarding technological and political components, several studies, including the findings of this study, have demonstrated that goals focused on these two areas are based on standards for operational effectiveness and efficiency: efficiency (%), technological development (on a qualitative scale), yearly energy production (in GWh), energy policy (on a qualitative scale), and political acceptance (on a qualitative scale). Because some studies concentrate more on the political aspects of assessing and choosing opportunities for sustainable food waste, this study demonstrated that policy coverage, acceptability criteria, and efficiency of food waste are still far from the global-scale criteria (Brennan *et al.*, 2021; Fesenfeld *et al.*, 2022). This topic should be considered when evaluating and choosing alternatives because it requires decisions to be made at all levels of government. The following criteria were determined for the environmental and social aspects: area of work (m^2), GWP, environmental impact (qualitative scale), employment generation (jobs/year), and social benefits (qualitative scale) (Kayaçetin and Tanyer, 2020; Soust-Verdaguer *et al.*, 2020). With sustainable food waste technology, these requirements imply limiting adverse effects on the environment and people's lives and optimizing socioeconomic impacts. To reduce global warming and other possible repercussions, nations including the United States, China, and India have concentrated on sustainable food waste research emphasizing environmental factors. Aspects connected to the Sustainable Performance Goals, as outlined by the 2030 Agenda established by the United Nations, such as Brazil and Taiwan, have highlighted the participation of people without access to sustainable distribution (Masood and Ahmad, 2021). Thus, the choice of criteria used to evaluate various sources of sustainable food waste will generally affect the outcomes of the MCDMA approach, including the importance of each criterion and indication in relation to how alternatives to sustainable food waste are chosen, sorted, and classified. Choosing indicators encompasses both issues pertaining to sustainability as a concept and those about various choices. To help decision-makers identify the most effective sustainability solutions, several criteria need to be more precisely defined and clarified. Consequently, the following hypothesis is proposed:

Proposition 2

Technological studies must address economic, political, technological, social, and environmental issues to implement sustainable food waste.

There are two primary ways to make decisions to choose the most profitable and effective option from various sustainable food waste technology solutions. The rationale for the manager's remuneration and non-compensation in expressing the choice determines which option is selected. The manager and analyst should engage in structured, interactive communication sessions as part of the decision-making process, during which the analyst records particular details regarding management preferences.

This study is pertinent to analyzing the research knowledge framework for various MCDMA methodologies and prospective KPIs. This analysis used a multi-criteria approach to evaluate, select, and rank sustainable food waste. This concept is based on sustainability. Application studies must be conducted to validate the approach and support its advancement, as well as to gather input on what else needs to be

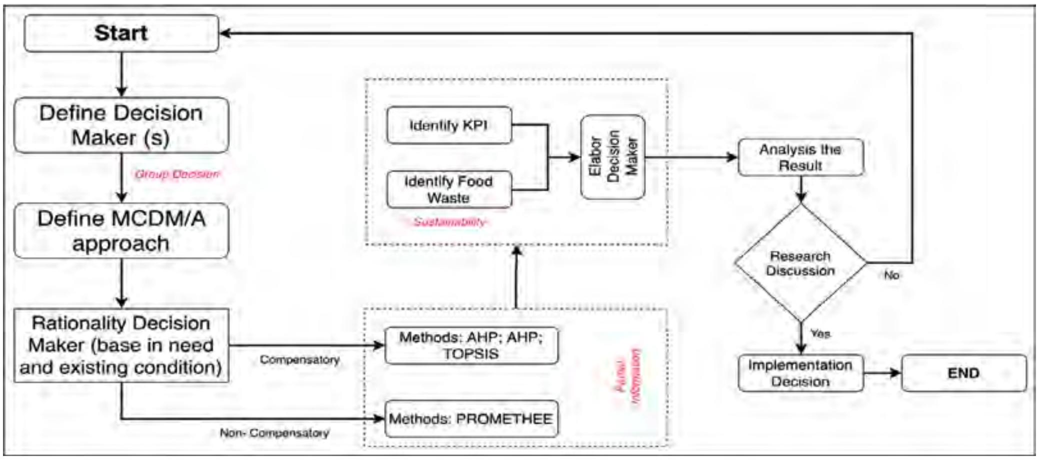

Fig. 12: Framework multi-criteria analysis method for sustainable food waste concept

produced in the study area. Using the findings of this study as a guide, sustainable food waste with a multi-criteria sustainability concept is recommended Fig. 12. Thus, the results of this study are as follows:

Proposition 3

The conclusions of this review allow the identification of options for a hybrid decision framework that combines the MCDMA approach with KPIs for recommendations.

RECOMENDATION

By collaborating together, promoting interdisciplinary cooperation among academics, professionals, and decision-makers in various sectors, including environmental science, food technology, economics, and social sciences, allows a better comprehension of the complex nature of sustainable food waste and improves the efficiency of bibliometric analysis and multicriteria decision-making. Studies of food waste have pushed for consistent data gathering and reporting procedures (Caputo *et al.*, 2023; Sachs, 2012; Solangi *et al.*, 2021). In addition, encouraging open-access databases and repositories containing pertinent bibliometric data allows more precise and repeatable academic analyses. Access to data is easier, resulting in more solid and trustworthy insights. A longitudinal bibliometric analysis was performed to identify emerging subjects, shifts in focus, and the effectiveness of interventions over time to follow the development of research trends. This strategy can highlight areas requiring more attention and the advancements in managing sustainable food waste. The opinions of diverse stakeholders, such as business leaders, government officials, and consumer advocacy organizations, are important in the bibliometric analysis and multicriteria selection process. Forging a holistic and lasting approach to resolving complex issues, such as food waste, requires the development of a strong decision-making policy that integrates environmental, economic, and social aspects. By integrating the capabilities of LCA, the policy may evaluate food waste management options from every perspective, including resource use, emissions, energy consumption, and potential ecological repercussions (Bolaji *et al.*, 2021). Simultaneously, the framework is permeated by a cost-benefit analysis that meticulously quantifies financial dynamics by weighing the expenses of implementing waste reduction methods against the benefits of reduced waste, resource conservation, and potential revenue streams. Notably, the policy highlights the necessity for a social impact assessment that investigates the effects of efforts to reduce waste on local communities, food security, and job creation. Based on the principles of fairness and equality, this factor guarantees that social effects are considered through due diligence. This all-inclusive strategy guarantees that recommendations and research findings correspond to real-world problems and priorities that exist in the real world. The significance of managing food waste sustainably can be increased through educational programs, workshops, and community engagement. Promoting broader knowledge of the difficulties and potential solutions related to food waste by disseminating the results of the bibliometric analysis to a larger audience. Recognizing sustainable food waste is a dynamic and evolving field. Bibliometric analyses are frequently reviewed and updated to reflect new research tendencies, develop new technologies, and shift management goals for food waste. Encouraging worldwide cooperation to exchange best practices, approaches, and discoveries from sustainable food research Cross-border collaboration between researchers and practitioners can foster the sharing of insightful ideas and creative solutions, accelerating the development of sustainable food systems. However, there is a complex web of difficulties in the areas of ecology, economy, and society that must be overcome if food waste management is to be sustainable. This strategy addresses multiple problems by decreasing food waste, disposing of it properly, and using it properly. In terms of the environment, it reduces the release of greenhouse gases, saves water and power, and protects species that might otherwise have been lost owing to development. To reduce poverty and malnutrition, it also seeks new uses for food that would otherwise be wasted. Wasteful spending costs households, corporations, and governments significant amounts of money. These initiatives also aim to educate consumers to change their habits and aid in optimizing supply chains. Sustainable food waste management promotes a move from the prevalent 'throwaway' mindset to a more mindful and resource-efficient paradigm, which requires a transformation in cultural norms and social attitudes toward food consumption. This comprehensive approach requires coordinated efforts across multiple disciplines to design sustainable food systems from multiple perspectives.

CONCLUSIONS

Integrating bibliometric analysis and multi-criteria decision-making can advance research, policies, and actions toward sustainable food waste management. Incorporating these techniques offers an extensive and thorough lens through which to evaluate the shifting landscape as civilizations navigate the difficult food waste issues within the global sustainability framework. Researchers can analyze the body of information on sustainable food waste using bibliometric analysis to identify major trends, influencers, and gaps. This analytical process gives stakeholders the knowledge necessary to effectively manage resources, promote collaboration, and prioritize research initiatives. It acts as a compass directing action toward increasingly significant research projects and fact-based choices. Combining bibliometric analysis and multicriteria decision-making offers a formal framework for assessing various aspects of sustainable food waste. Decision-makers can holistically evaluate interventions and strategies by concurrently considering environmental, economic, social, and ethical criteria. The identification of the best routes that support sustainability objectives and encourage constructive change throughout the food supply chain is made possible by this methodical methodology. The combination of these techniques exceeds theoretical investigations and results in practical advice for application in actual situations. Stakeholders have the information necessary to create and implement laws, customs, and technological advancements that significantly reduce food waste and negative environmental effects and improve resource efficiency. This investigation highlights the expanding awareness of the complex interplay among environmental, economic, and social factors in the food waste crisis. Multi-criteria decision-making methods have become increasingly popular in the research community as a strong framework for addressing this complexity. Food waste, a multi-criteria model, economic, environmental, and social factors, policy considerations, and technical feasibility were some of the factors considered in this study. This makes it easier for decision-makers to understand the complex trade-offs and synergies involved in long-term food waste management. This analysis highlights the increasing commitment to comprehensive solutions that focus on waste reduction as well as resource efficiency, environmental stewardship, and societal well-being as sustainable food waste management gains traction on global agendas. However, these data indicate a need for further investigation. Metadata like keywords and abstracts affect results; therefore, data quality and coverage are crucial. The use of published literature may exclude unpublished or non-English sources and distort trends. Bibliometric statistics may not adequately reflect current trends because of the changing nature of study fields. Citations may not accurately reflect a paper's influence; therefore, their interpretation may be complicated. Owing to database disciplinary categorizations, multidisciplinary research may be underrepresented. The implementation of advanced MCDMA models requires computational resources and skills. Criteria weights are difficult to determine because stakeholder preferences vary, and consensus may be difficult. The assumptions and capabilities of multiple models make it difficult to select an MCDMA method. Finally, the interpretability of sophisticated MCDMA models may inhibit communication and decision-making, highlighting the complexity of these issues. Future research should focus on eliminating inequalities in the use of multi-criteria decision-making across regions, industries, and stages in the food supply chain. Furthermore, interesting directions for progress in this area include the incorporation of developing technologies and innovative techniques into established methodologies.

AUTHOR CONTRIBUTIONS

Syafrudin oversaw the idea, methodology design, and information gathering for the bibliometric analysis, giving a solid insight of the current state of the field. I.B. Priyambada was instrumental in developing the multicriteria decision-making framework, analysing the data, and making insightful amendments to the text. The data collection and organization, the multicriteria decision-making analysis, and the transformation of complex outcomes into illustrative visual representations were all made possible thanks to the contributions of M.A. Budihardjo. Through a comprehensive examination of the literature, data interpretation, and visualization support, S. Al Qadar provided insightful information. As the project's supervisor, A.S. Puspita assisted with project management, gave advice throughout the research process, obtained funding, and helped to polish the final manuscript.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS

%	Per cent
$	Dollar
AD	Anaerobic digestion
AF	Animal feed
AHP	Analytical hierarchy process
AI	Artificial intelligence
Bc	Bio conversion
Bs	Biogas
BSF	Black soldier fly
CE	Circular economy
CO	Carbon monoxide
COMP	Composting
DEA	Dara envelopment analysis
ELECTRE	Elimination et choix traduisant la rEalite
EIA	Environmental impact assessment
EPA	Environmental protection agency
FAO	Food and agriculture organization
GRA	Gray relational analysis
Gs	Gasification

GWP	Global warming potential
GwH	Gigawatt Hour
INC	Incineration
IoT	Internet of Things
IVC	In vessel composting
KPI	Key performance indicators
kWh	Kilowatt-hour
LCA	Life cycle assessment
LCC	Life cycle cost
LF	Landfilling
M^2	Square meter
MCDMA	Multicriteria decision making aiding
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PCA	Principal component analysis
RYCL	Recycle
RPIBT	Riset publikasi internasional bereputasi tinggi
SAPBN UNDIP	Selain anggaran pendapatan belanja negara universitas diponegoro
SLCA	Social life cycle analysis
SWOT	Strengths, weaknesses, opportunities, and threats
SD	System dynamics
TOPSIS	Technique of order preference by similarity to ideal solution
UN	United Nations
VIKOR	VIseKriterijumska optimizacija I kompromisno resenje
WB	Waste bank

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SPECIAL ISSUE: (Eco-friendly sustainable management)
CASE STUDY

Analysis of environmental health risks from exposure to polyethylene terephthalate microplastics in refilled drinking

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ABSTRACT

BACKGROUND AND OBJECTIVES: Microplastic pollution has a far and wide presence in the surroundings. It can be encountered in the sea, wastewater, freshwater, food, air, and water sources. It is even present in refilled drinking water. This study aims to analyze environmental health dangers of the exposure to polyethylene terephthalate microplastics in refilled water sources in Tamangapa, Makassar City, Indonesia.
METHODS: This research is an observational study with an environmental health risk analysis. Sampling was conducted in Tamangapa, Makassar City, Indonesia. A total of 100 respondents were involved. Additionally, 20 samples of refilled drinking water were examined in the laboratory using the Fourier Transform Infrared test. Data analysis was carried out by calculating the intake and risk quotient values. If risk quotient > 1, it is considered necessary to carry out risk management.
FINDINGS: An average polyethylene terephthalate microplastic concentration of 0.0052 milligram per kilogram per day, an average intake rate of 210 milligrams per kilogram per day, an average exposure frequency of 350 days, an average exposure duration of 30 years, average intake exposure to polyethylene terephthalate microplastics above 0.0004, and an average risk quotient value above 1 were obtained. If they build up in the body, microplastics may have harmful consequences, including organ inflammation, internal or external damage, and chemical alteration of plastics that have already entered the body.
CONCLUSION: Some measures of risk management that can be performed are to reduce the concentration of risk agents if the pattern and timing of consumption cannot be changed, reduce the consumption pattern (intake rate) if the concentration of risk agents and the time of consumption cannot be changed, and reduce the contact time if the risk agent concentration and consumption pattern cannot be changed.

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60	7	5

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INTRODUCTION

Plastic is a collection of synthetic or man-made organic compounds that can be transformed into various shapes, sizes, colors, and densities (Hesselink *et al*., 2019). The world's plastic products have reached 360 million tons. Asia is the region with the most significant growth in plastic waste production in the world, reaching a level of 51 percent (%) (Plastic Europe, 2019). Particularly, Indonesia is the world's second-largest producer of marine plastic debris, after China, reaching 262.9 MT of plastic annually (Monteleone *et al*., 2019). Every year, Indonesia dumps as much as 0.48–1.29 million metric plastic waste into the sea, which is also the second highest in the world (Jambeck *et al*., 2015). This number increases yearly in line with the increasing demand for plastic by the public (Hoegh *et al*., 2015). Microplastic pollution has a far and wide presence in the environment (Manatura and Samaksaman, 2021; Takarina *et al*., 2022). It can be encountered in the sea, sewage, clean water, food, air, water sources, and even in drinking water, including refilled drinking water (Wagner and Lambert, 2017). Microplastics come from plastic waste that is improperly handled and thrown away into the environment (Ayuningtyas, 2019; De Sliva *et al*., 2021). One of the factors that increase the possibility of microplastic contamination in drinking water is weak control over the quality of drinking water during the production process, both for water in single-use bottles and for water in multiple-use bottles (Handayani, 2020). Based on research results by Kasmini and Batubara (2023), of 500 oyster samples collected, 139 were contaminated with microplastics. The most dominant type of microplastic contamination in oysters is fiber contamination, with up to 170 particles found, followed by contamination in the form of films and fragments, each with 28 particles and 19 particles. The results of this study revealed that oysters consumed by people have been contaminated with microplastics. The study hypothesized that microplastics are present in refilled drinking water and cause contamination in it. Microplastics can enter the freshwater environment in various ways. They originate from, among other sources, degraded plastic waste (Isma and Danira, 2022). Microplastics were found in refilled drinking water depots with an abundance of 0.8 (particles/L) in line shapes, red and blue in color, and 1.02–1.491 millimeters (mm) in size (Machrany *et al*., 2021). In bottled drinking water, microplastics were found in the form of fragments of the polypropylene type at 10.4 particles/L in sizes > 100 micrometers (µm), and at 335 particles/L in sizes between 6.5 µm and 100 µm (Isma and Danira, 2022). Polyethylene terepthalate is a linear thermoplastic polymer consisting of repeating units of terephthalic acid and ethylene glycol monomers (Yoshida *et al*., 2016). PET, polyurethane, polystyrene (< 10% each), polyethylene (36%), polypropylene (21%), and polyvinyl chloride (12%) are involved in the production of non-fiber plastics. The production of non-fiber products requires polyesters, including 70% PET (Geyer *et al*., 2017). Water supplies or groundwater are contaminated by PET plastic or the substances it has leached. Numerous studies have shown the migration of microplastics from PET plastic into the water. The pH levels and scent strength of the military water that was packed in PET were examined and recorded. After long-term water storage, it was discovered that these were higher than the US Food and Drug Administration's (USFDA) and US Environmental Protection Agency's (USEPA) recommended limits (Greifenstein *et al*., 2013). Microplastic particles of this type that measure 50 µm can translocate to the liver or spleen through the lymph, posing a risk of inflammation and changes in immune processes (Nirmala *et al*., 2023). Currently, there are only a few studies focused on microplastic contamination in drinking water. Weak supervision opens up opportunities for drinking water to be easily contaminated with microplastics as it goes through production stages, for example, during the processes of sterilizing, washing, rinsing, and sealing drinking water packaging (Handayani, 2020). Therefore, this study offers a reference for researchers to conduct research on the health risks of exposure to polyethylene terephtalate microplastics in refilled drinking water in Tamangapa, Makassar City. The purpose of this study is to analyze the average level, intake rate, frequency of exposure, duration of exposure, daily intake level (intake), level of risk (risk quotient), health risks, and risk management of the exposure to polyethylene terephthalate microplastics in refilled drinking water in Tamangapa, Makassar City, Indonesia in 2023.

Fig. 1 shows the refilled drinking water sampling location in the Tamangapa, Manggala District, Makassar City, Indonesia. The location covers a total

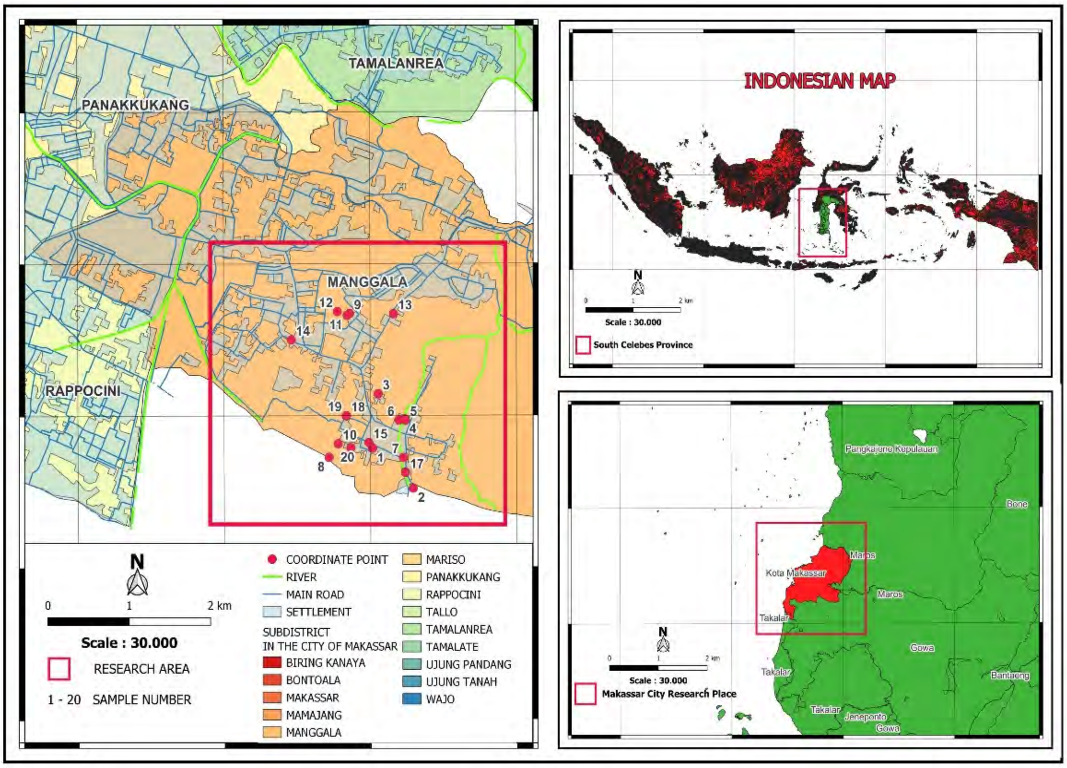


Fig. 1: Geographic location of the refilled drinking water sampling location in the Tamangapa, Manggala District, Makassar City, Indonesia

area of 662 square kilometers (km[2]), equal to 66,200 hectares (ha). Previous study was carried out by machines in Tamangapa village, Makassar city. The location covers a total area of 662 square kilometers (km2), equal to 66,200 hectares (ha) by taking six air samples, of which three samples came from residents' homes and three air samples from depots).

Fig. 2 shows that the highest rainfall of 765 mm was in January, and the lowest rainfall of 8 mm was in July. Indonesia is classified as a tropical country. The average temperatures of warm waters in the Indonesian territory are 28 °C, 26 °C, and 23 °C in coastal areas, inland and highland areas, and mountainous areas, respectively.

MATERIALS AND METHODS

Sample collection

Samples of refilled drinking water in this study were taken at the research location, Tamangapa, Makassar City. A total of 20 refilled drinking water samples were taken directly from depots or residents' homes. The non-probability convenience sampling method, which is commonly used to overcome unwanted limitations in small- to medium-scale research, was employed in this study (Taherdoost, 2016).

Sample preparation

Before use, all pieces of equipment were washed with 10% nitric acid and rinsed with aquabidest to avoid contamination from the equipment. Refilled drinking water samples were prepared at 1,000 ml and given 2 drops of 0.1% Nile Red dye solution, then they were incubated for about 30 minutes. Nile Red dye solution will be adsorbed on the surface of microplastics, but not on most natural materials, making microplastics visible under a microscope with a magnification of 100× to 400×. For characterization with FTIR (Fourier Transform Infrared) test materials were filtered first using a cellulose nitrate filter with a specified weight and a pore size of 0.45 µm. The residual weight can be calculated to determine the microplastic content quantitatively with aquabidest

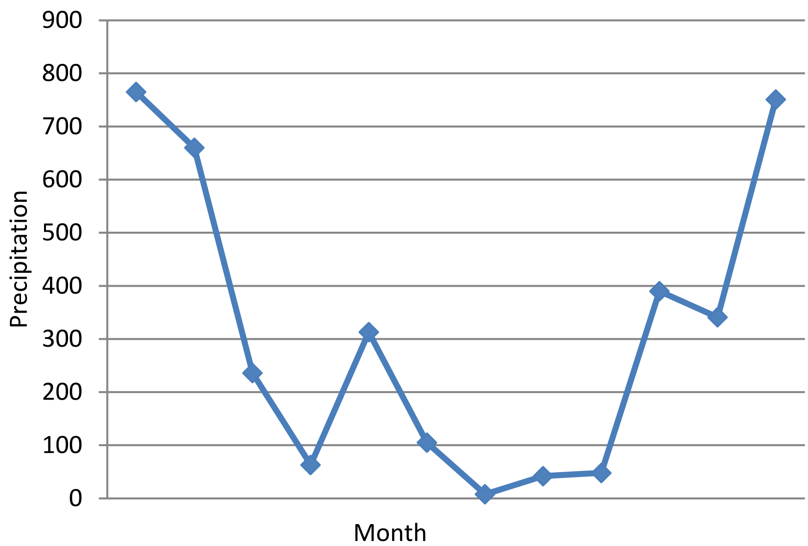


Fig. 2: The rainfall from January to December.

as a standard blank (Taherdoost, 2016).

Determination of the mass and concentration of microplastics

Initially, filter paper with a pore size of 0.45 µm was used to filter aquabidest as a blank. Then, it was dried in a desiccator for 24 hours. After drying, the filter paper was weighed, and the mass was recorded. The water samples were then filtered with the filter paper. The filter paper was once again dried in a desiccator for 24 hours after filtering was finished. After drying, the filter paper was weighed again, and the mass was recorded. The difference between the volume of filter paper after filtering and the initial mass was the mass of the microplastics accommodated on the filter paper. This microplastic mass represents the concentration of microplastics in each liter of water that went through the filtration process (Taherdoost, 2016).

Characterization of the number of microplastic particles

For morphological analysis (fragments, fibers, pellets, films, etc.), the residue on the filter was examined under an optical microscope (Leica ICC50 HD) with 100× and 400× magnification. In addition to morphological analysis, an examination under an optical microscope using the modified Neubeuer Improved Counting Chamber method was also carried out to count the number of particles per sample volume. This method is an accurate method that is commonly used to measure the number of cells/particles in biological fluids. In this method, observations with a microscope are carried out on samples positioned in a given space (0.1 mm). Then, the quantity of particles observed in the sample volume is counted. In this study, the results of this calculation were converted into units of the amount of debris per liter of the sample, with the assumption that the samples were homogeneous, i.e., the drinking water samples were homogeneous solutions. Furthermore, the microplastic residue filtered on the cellulose nitrate filter with 0.45-micrometer pores was measured by Fourier Transform Infrared (FTIR) with a pure polymer standard. FTIR characterization is a chemical examination method used to establish the identity of a compound in a sample (Samimi and Mansouri, 2023). The identity of a compound can be recognized from its functional groups, namely, the types of bonds between different atoms, which are the part that distinguishes one compound from another (Samimi and Shahriari-Moghadam, 2021; Samimi and Safari, 2022). This FTIR characterization can identify functional groups in compounds by reading the infrared light signals transmitted by the compounds in samples, which occur in the FTIR instrument used (Dutta, 2017; Ehzari *et al.*, 2022; Samimi and Shahriari-Moghadam, 2023).

FTIR microscopy

The molecular make-up of plastic particles may be determined by combining vibrational spectroscopy with optical microscopy and/or SEM. To prevent the development of unsettling peaks in the spectrum, it is often crucial to remove the suspected microplastic particles from the sample matrix since the signal intensity acquired relies on the size of the particles investigated (Nguyen *et al.*, 2019). FTIR micro-spectroscopy is an efficient and popular technique for locating microplastics. The signal is reliant on changes to the molecule dipole moment brought on by molecular vibrations. The molecule is brought to a higher vibrational state by absorbing IR light, and this state is precisely correlated with the kind of bonds that are present in the molecule under investigation. Contrary to scanning electron microscope-energy dispersive X-Ray, infrared spectroscopy is a very effective technique for obtaining fingerprint data on the sample's molecular composition and the particular bonds that are present (Gurumurthy *et al.,* 2017). An FTIR microscope's spatial resolution is only 10–20 m, despite being wavelength-specific and subject to established diffraction restrictions. For FTIR to function correctly, ideally, samples should be stored on a substrate that is transparent to IR and has a thickness of at least 150 nm. This limitation makes FTIR most effective for particles bigger than 20 m in size. It is still possible to analyze aggregations or films of smaller particles (Chen *et al.*, 2020). Because it is better than other technologies at detecting microplastic particles as tiny as 20 m, micro-FTIR spectroscopy (micro-FTIR) is an ideal tool for identifying microplastics in the air. IR is a region belonging to the electromagnetic spectrum between the microwave and visible light regions. FTIR spectroscopy, which takes the form of molecular fingerprinting, is typically applied in the constrained frequency range between 4,000 and 400 cm^{-1} (wavenumber), as it is this "fingerprint" region that offers practical value for identifying bonds, even though the IR region spans in wavelength from about 700 nm to 1 mm. It is possible to observe the existence of distinctive atoms or atomic groupings and, as a result, ascertain the composition by comparing the infrared spectra of diverse materials.

Time and place

Sampling was conducted in Tamangapa Village, Makassar City. The populations in this study were people who consumed refilled drinking water and all refilled drinking water depots located in Tamangapa Village, Makassar City. This study involved 100 respondents, who were sampled using a purposive sampling technique, and 20 water samples taken directly from depots.

Data analysis

In this study, the environmental health risk analysis (ARKL) was implemented in the following stages:

a. Hazard identification

In this stage, the type of polyethylene terepthalate microplastic polymer contained in refilled drinking water was determined.

b. Dose-response analysis

A dose-response analysis was carried out based on the standardization issued by the US-EPA Agency for the reference dose (RfD) value of polyethylene terepthalate microplastics, which is 0.0004 milligram per kilogram per day (mg/kg/d). Calculation was performed using Eq. 1 (USEPA, 2020).

c. Exposure analysis

$$I = \frac{\text{C x R x fE x Dt}}{\text{Wb x t avg}} \quad (1)$$

Where;

I (Intake)	The total concentration of risk agents that enter the human body with a certain body weight (kg) every day (mg/kg/day)
C (Concentration)	The concentration of the risk agents of polyethylene terephthalate microplastics in refilled drinking water (mg/l)
R (Rate)	The rate of consumption or the volume of water that enters the human body every day (mg/l)

fE (Frequency of Exposure)	The length or number of days (days/year) of exposure to microplastics each year (350 days/year for residential default value)
Dt (Duration)	The duration or number of years of exposure
Wb (Weight of Body)	Human body weight/ population/group
t avg (Time Average)	Average time period (30 years × 365 days/year for non-carcinogenic effects and 70 years × 365 days/year for carcinogenic effects)

d. Risk characterization

Risk characterization for non-carcinogenic effects was carried out by dividing intake by the dose or concentration of risk agents using Eq. 2 (USEPA, 2015).

$$RQ = \frac{\mathrm{I}}{\mathrm{RfD}} \quad (2)$$

Where;
RQ: Risk characterization
RfD: Response concentration analysis
I: Intake (exposure)

Microplastics: Origins and routes toward drinking water

Drinking water sources are mostly contaminated by microplastics (both primary and secondary) due to surface runoff and wastewater/wastewater treatment plant waste discharge. There are a large number of industries using microplastics (primers) for various applications, including pharmaceuticals, make-up, etc. These principal microplastics are flushed away after usage and end up in home wastewater (Surya *et al.,* 2021). Some of the microplastics in bottled drinking water come from the packaging and or

Table 1: Comparison of microplastic analysis techniques

Methods	Advantages	Limits
	Scanning electron microscopy (SEM)	
An intense electron beam is used to scan the sample's surface. Images may be produced thanks to the sample's electron beam scattering.	This technique provides high-resolution (0.5 nm resolution) images of the sample.	Samples must be prepared for observation; the type of polymer cannot be identified; instrument acquisition is expensive; it is an old-fashioned analysis.
	Raman spectroscopy	
Inelastic scattering takes place when laser energy strikes the object. The frequency shift between two beams may be used to assess the chemical makeup of a sample.	It is a reliable method for identifying microplastics; it can detect microplastics down to 1 µm in size; it causes no damage; it can analyze solutions and tolerate the presence of water.	Samples must be properly prepared to isolate important microplastics; It can be affected by additives, dyes, impurities, and the background fluorescence of the sample; data acquisition can take time; It takes costly equipment, and without standards, understanding data could be challenging.
	Fourier transform infrared spectroscopy	
The sample is exposed to infrared light, and the spectrums of its transmission or absorbance then contrasted with those of samples that are known.	It is reliable; it causes no damage; micro-FTIR can study particles down to 20 µm in size; it can determine the MP composition; it is able to map the surface of large samples.	The accuracy will suffer when the target particle is smaller than 20 µm, expensive equipment is needed; the sample must be processed or purified to remove matrix interferences; the spatial resolution of detection is limited by the radiation's wavelength, and the best resolution is down to tens of microns; water is also impossible to detect.
	Optical microscopy	
The preparation and identification of samples is done under an optical microscope.	Quick screening is feasible; it is the cheapest of all techniques; it is able to detect the size, shape, and color of MPs; it is easy to identify non-plastic particles when recognized.	It lacks qualitative chemical identification; it bears polymer error potential for inorganic materials; optical microscopes may miss small particles.

Table 2: Worldwide reported contamination of microplastics in drinking water (Surya *et al*., 2021)

Water type	Identification methods	Size range (Mm)	Concentration (Particles/L)	Shape	Composition	Sources
Source of drinking water (groundwater)	FTIR spectroscopy	50 – 150	0 – 7	Fragment	Polyethylene, polyamide, polyester, polyvinyl chloride	Mintening *et al*., 2019
	Pyrolysis–GCMS	-	6.4	Fiber	Polyethylene	Panno *et al*., 2019
Water treatment from a water treatment plant	FTIR spectroscopy & micro Raman imaging microscopy	1–10	338±76 to 628±28	Fragment, Fiber	Polyethylene terephthalate, Polypropylene, Polyethylene	Martin *et al*., 2018
Tap Water	FTIR spectroscopy	100 – 5.000	0 – 61	Fiber	-	Kosuth *et al*., 2018
Plastic water bottle						
	FTIR spectroscopy	6.5 - >100	0 to 10.000	Fragment	Polypropylene	Mason *et al*., 2018
		-	3.57	Fiber	-	Kosuth *et al*., 2018
	Micro FTIR spectroscopy	5 – 20	118±88 (returned bottle 14±14 (single use bottle)	Fragment	Polyethylene terephthalate, Polypropylene	Darena *et al*., 2018
	Micro Raman spectroscopy	< 5	4,890±5,430 (returned bottle 2,649±2,857 (single use bottle)	-	Polyethylene	Oßmann *et al*., 2018
Glass water bottle	FTIR spectroscopy	6.5 – 1.410	14.8(.100µm)	Fragment, fiber	-	Mason *et al*., 2018
		>100	1,396(6.5–100µm)	Pellet, film, foam	-	
	Micro FTIR spectroscopy	> 100	50±52	-	Polyamide, Polyethylene, Polypropylene	Darena *et al*., 2018
	Micro Raman spectroscopy	< 5	6.292±10.521	-	Polyethylene, Styrene–butadiene–copolymer	Oßmann *et al*., 2018
Carton bottled water	Micro FTIR spectroscopy	> 100	11±8	Fiber	Cellulose, Polyethylene, Polypropylene	Darena *et al*., 2018

bottling process itself. Otherwise, contamination can also come from raw water sources, packaging materials, washing machines, or the circuit in the process of filling water into packaging. Microplastics contamination in refilled drinking water can come from the management process which uses equipment or pipes made of plastic such as polyvinyl chloride, polypropylene, and polyethylene (Mason *et al*., 2018). The effluent produced from wastewater treatment facilities includes considerable levels of contamination as these facilities lack the tools required to completely remove microplastics (Amrutha *et al*., 2020). Once this waste is mixed with freshwater sources, microplastics are introduced into the clean/drinking water supply chain (Elvis *et al*., 2019). A case in point is that the increased concentrations of microplastics in the Chicago River were reportedly caused by effluents from local sewage treatment facilities (Amanda *et al*., 2014). It is also crucial to remember that a lot of the parts of water purification and distribution systems often comprise plastics like high-density polyethylene, polyvinyl chloride,

Table 3: Distribution of Respondent Characteristics in Tamangapa, Manggala District, Makassar City 2023

Variable	Frequency (n)	Percentage (%)
Gender		
Male	58	58
Female	42	42
Age		
< 12 years	40	40
12–40 years	3	3
41–60 years	55	55
> 61 years	2	2
Level of education		
Elementary school	43	43
Junior high school	15	15
Senior high school	20	20
College	22	22
Type of work		
Not yet working	43	43
Housewife	15	15
Government employees	20	20
Self-employed	22	22
Weight		
< 30 kg	27	27
31–60 kg	31	31
> 60 kg	42	42

and polypropylene (Mintening *et al.*, 2019), which can also aid in the development of microplastics in the water they transport. Environmental elements, each with unique environmental properties, such as sunshine, temperature, and air/oxygen, among others, have a big effect on how microplastics break down into (secondary) microplastics (Weinstein *et al.*, 2016).

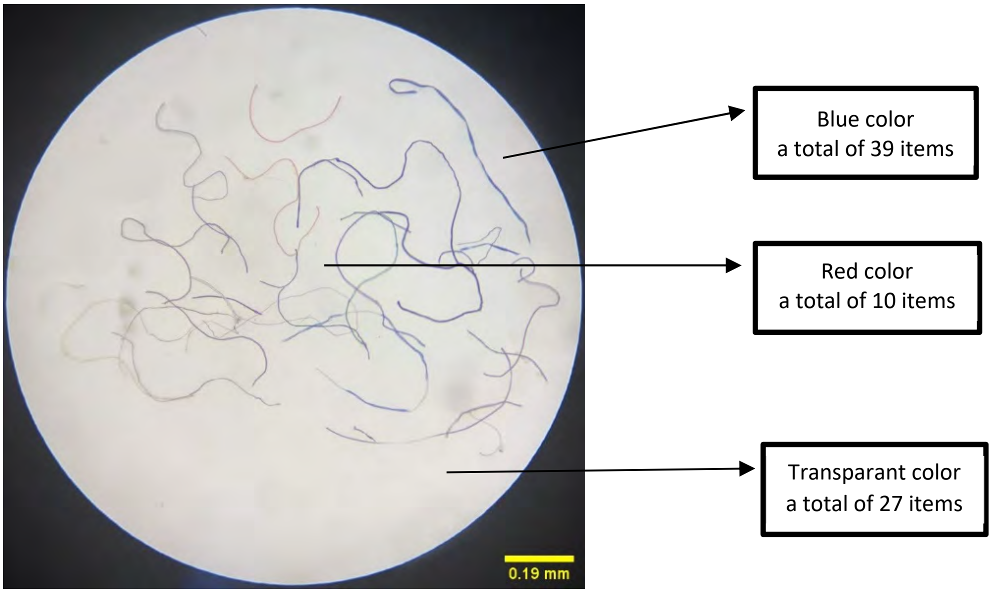
RESULTS AND DISCUSSION

According to Table 3, the male respondents outnumbered their female counterparts (58 males or 58% of all respondents), the most vulnerable respondents were in the 40–60 years age group (56 people or 55% of all respondents), and the education level of the majority of respondents was elementary school (43 people or 43% of all respondents). Forty-two percent of all respondents weighed above 60 kg, and 27% weighed under 30 kg.

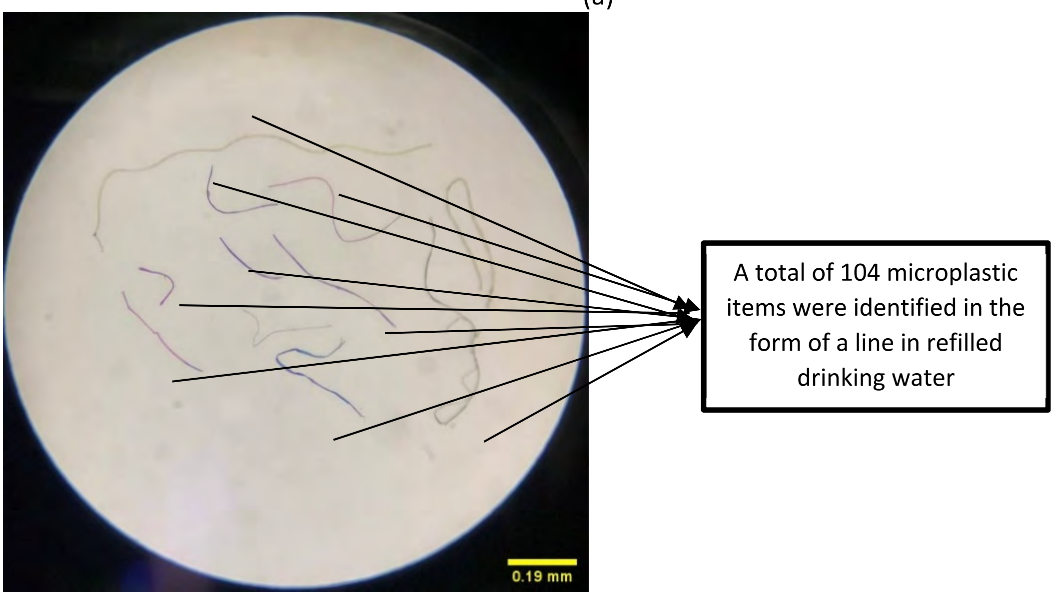
Body weight reflects nutrients in the human body; people with an ideal body weight are sufficiently nourished (Sartika, 2008). Low body height or weight can be influenced by nutritional intake into the body and physical activity. In a study, it was found that the toxic substance in the body is inversely proportional to body weight because the greater the body weight, the wider the toxic substance distribution in the body (Girikallo *et al.*, 2022). An individual with a great body weight has more fat contained in the body (Zhang *et al.*, 2020).

Fig. 3 depicts the results of observing and identifying microplastics in refilled drinking water from depots in Tamangapa, Manggala District, Makassar City, under a microscope with a 45× magnification. The correlation between the type and size of detected PET microplastics is directly proportional to the specific source of refilled drinking water. Microplastics were found in refilled drinking water depots at 0.8 particles/L in the line shape, red and blue in color, and 1.02–1.491 mm in size (Machrany *et al.*, 2021).

Fig. 4 displays the levels of microplastics in the 20 samples of refilled drinking water examined at the Ecotoxicology Laboratory of the Faculty of Fisheries and Marine Sciences, showing a maximum concentration of PET microplastic contamination of 0.030 mg/kg and a minimum of 0.001 mg/kg. Based on the results of laboratory tests, different microplastic concentrations were obtained because the levels of microplastic particles differed for each sample. The path that PET microplastics in refilled drinking water take into the body can impact on human health. PET microplastics may go into the body through the ingestion route, that is, when they are ingested and enter the body through the gastrointestinal tract.



(a)



(b)

Fig. 3(a) and (b) Color and total number of microplastic particles in refilled drinking water

Foods and drinks contaminated with microplastics are considered one of the primary forms of human exposure to microplastics. Microplastics are defined as particles that are less than 5 mm in diameter and consist of polymers (Storck *et al*., 2015). By source, primary and secondary microplastics are the two categories into which microplastics fall (Zhang *et al*., 2020). The microplastics contained in bottled drinking water partially come from the packaging and/or the bottling process itself (Mason *et al*., 2018). In refilled drinking water, microplastic contamination can come from the management process that uses equipment or pipes of plastic such as polyvvynyl chloride (PVC), polypropylene (PP), and polyethylene (PE). Based on

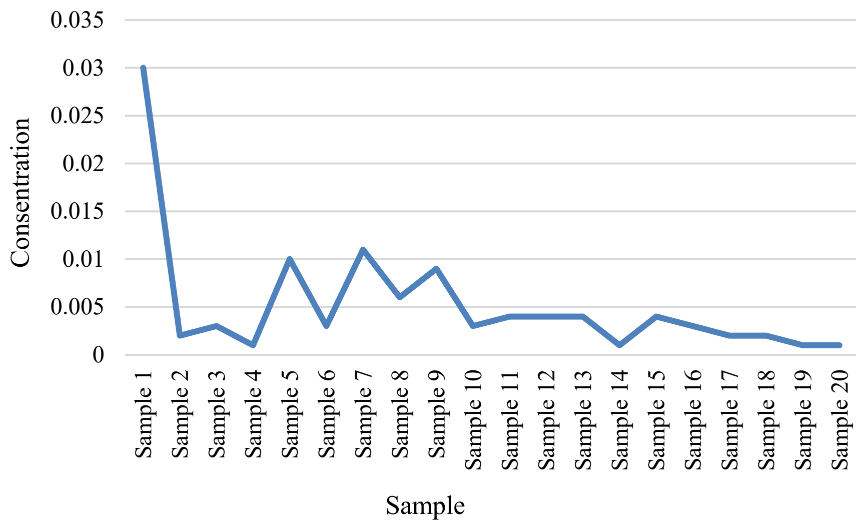


Fig. 4: Concentration of microplastics in refilled drinking water

test results and the reading of the type of polymer from the FTIR analysis, microplastics were found to be in the line form. A student at the University of North Dakota (UND) measured the concentrations of microplastics in water containers, bottled water, and locally produced soft beverages on campus. The results showed that microplastics were present in the bottled water samples at an average of 101 particles/liter (Abdulmalik and Mansurat, 2019). This quantity is smaller than the microplastics content of the samples from the cask and soft drink. The most prevalent form of microplastics was that of a fragment (Savitri, 2015).

The use of FTIR analysis allowed for the detection of microplastics. PVC, PP, PET, PS, HDPE, and LDPE were discovered in the samples after comparison of the FTIR spectrum data with electronic spectrum libraries. FTIR spectroscopy (Thermo Fisher Scientific-US) is often used for the chemical identification of suspected microplastic particles, even when they may be visually detected by optical microscopy. Table 4 shows that the ages (years) of the respondents ranged from 7 years to 68 years, with a median value of 50 years. The respondents' body weights ranged from 21 kg to 73 kg, with a median value of 57 kg. The respondents' intake rates ranged from 126 mg/kg/day to 269 mg/kg/day, with a median value of 210 mg/kg/day. The frequency of exposure refers to how much the respondent consumed refilled drinking water. Interview results revealed that all respondents consumed refilled drinking water. Study results by Abdulloh (2020) showed that by type, of all the refilled drinking water samples investigated, 25 samples contained HDPE microplastics, 13 samples contained PVC microplastics, and 11 samples contained PE microplastics. By shape and color, 159 blue fiber particles, 130 red fiber particles, 67 transparent fiber particles, and 35 yellow fiber particles were found.

The greater the frequency of exposure, the greater the level of risk due to microplastic exposure. If one has an exposure frequency of 350 days, then he/she will most probably have a high intake (I) value. The more often and the longer an individual is in a polluted environment, the greater the number of agents likely to enter the body and the greater the risk of health problems occurring (Juwitriani *et al.*, 2016; Samimi *et al.*, 2023). The average value increases beyond the consumption of refilled drinking water because the level of human need for drinking water varies. Every human being requires drinking water in the amount of at least 8 L/day. Prolonged exposure to polyethylene terephathalate microplastics contained in refilled drinking water will cause an accumulation of microplastics in the body. The longer an individual is exposed to a hazardous substance, the greater his/her likelihood of being exposed to a health risk. Although in a low concentration, the accumulation resulted will cause health effects in the long term (Rochman *et al.*, 2016). As shown in Fig. 6, the mean

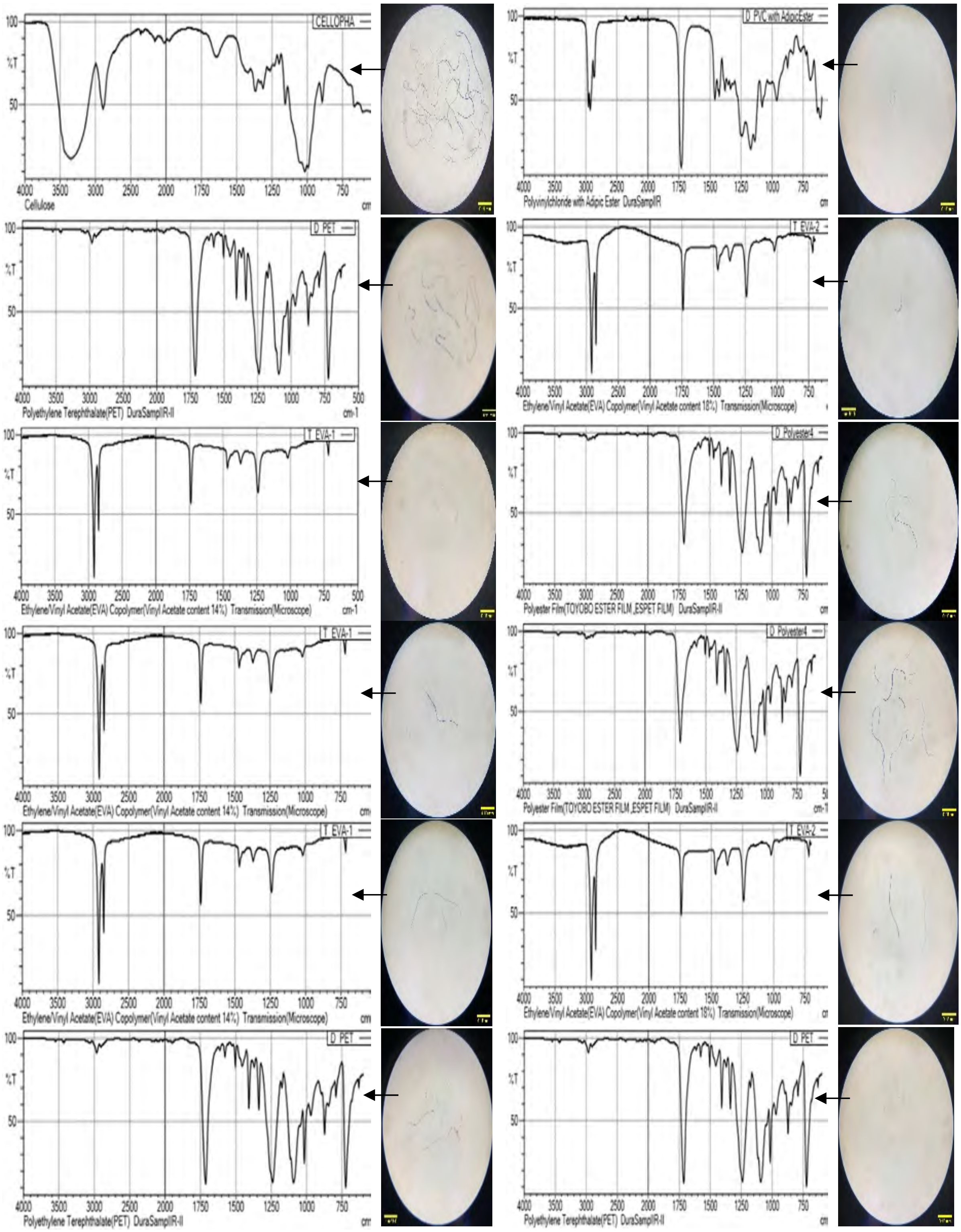


Fig. 5: Results of the FTIR analysis of the microplastics in refilled drinking water

Table 4: Characteristics of respondents based on risk analysis and community activity patterns in Tamangapa, Manggala District, Makassar City

Indicator	Min	Max	Median	Information
Age	7	68	50	Years
Weight	21	73	57.50	kg
Intake Rate	126	269	210	mg/kg/day
Frequency of Exposure	350	350	350	day/years

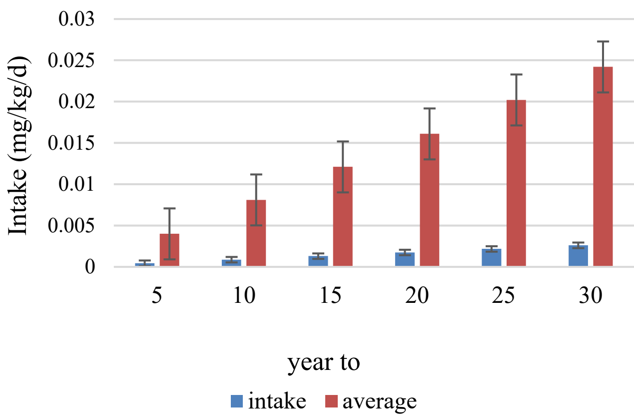


Fig. 6: Projected mean intake of polyethylene terephalate microplastics during 30 years of exposure time

intake of PET microplastics in Tamangapa, Makassar City, is projected to continuously increase from the 5th to the 30th year, with microplastic intake values between 0.000434 and 0.002607. Smaller fractions of ingested microplastics (1–10 µm) can be absorbed in the intestinal area and trapped in the human body throughout life. In cases where excretion of bile is limited, the trapped particles will reach a higher concentration in all body tissues than in the intestine despite the small particle size.

Estimates were made of the MP intake levels in salt, the water, and the air. The median and maximum microplastic consumption recorded for salt and the air were close to the 90th percentile. The readings recorded for tap water, however, were below the 50th percentile of the distribution range (Siswati and Khuliyah, 2017). The relationship between intake and risk agent concentration, exposure frequency, and exposure duration is linear. In other words, the greater the values of these variables, the greater the individual's intake. The longer the individual drinks contaminated refilled drinking water, the greater the intake value and the greater the risk for adverse health effects (DGDCEHMH, 2012).

Fig. 7 shows the projected risk quotient for the exposure duration of 5–30 years on microplastics (polyethylene terephalate) in Tamangapa, Makassar City, which always increases, exceeding the reference dose in the next 5–30 years. RQ > 1 indicates that the level of risk is unacceptable or unsafe, which necessitates controlling risk in order to drive the RQ down below 1. The average non-carcinogenic risk quotient calculation was higher due to differences in body weight. Toxicity will affect those with low body weights more easily than an individual with a high body weight. In other words, the greater the body weight, the lower the risk of suffering from non-carcinogenic diseases. The level of risk will increase with the increasing duration of exposure or estimated time. Table 5 shows that the risk management that must be carried out against PET microplastic exposure is projected to span 5–30 years in duration of exposure, with a minimum value of 2.52E+08, a maximum value (Max) of 2.47E+10, and an average value of 6.48E+09. For the intake rate, the minimum value (Min) is 4.29E+07, the maximum value is 3.27E+09, and the average value (Mean) is 2.52E+08. As for reference doses, the minimum value (Min) is

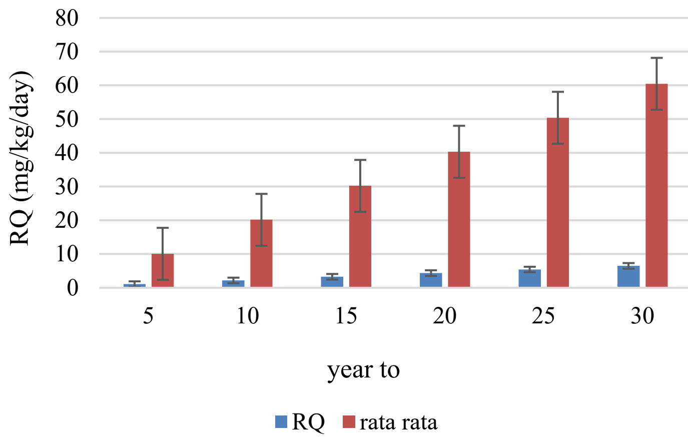


Fig. 7: Projected mean risk quotient of polyethylene terephalate microplastics during 30 years of exposure time

Table 5: Minimum, maximum and mean risk management values in Tamangapa, Manggala District, Makassar City

Variable	Risk Management (mg/kg/day)		
	Min	Max	Mean
Duration time	2.52E+08	2.47E+10	6.48E+09
Intake rate	4.29E+07	3.27E+09	2.52E+08
Reference dose	3.13E+05	2.90E+07	2.90E+06

3.13E+05, the maximum value (Max) is 2.90E+07, and the average value (Mean) is 2.90E+06.

The degree of risk is stated in numbers without units as a result of computing the ratio of intake to reference dose/concentration of a non-carcinogenic risk agent, which may also be regarded as either a safe or an unsafe risk agent for organisms, systems, or populations (Darena, 2018). When microplastics are ingested, the addictive substances and absorbed chemicals can be released in digestive juices and potentially transfer to edible tissues (Campanale *et al.*, 2020). Particles smaller than 150 µm can enter through the gastrointestinal epithelium of mammals and cause systemic exposure. However, scientists hope that only 0.3% of these particles be absorbed (A'yun, 2019). If microplastics accumulate in the body, they can have negative impacts such as inflammation of the organs, internal and/or external injuries, transformation of plastic chemical contents into the body, intestinal microbial disturbances that cause blockage of the intestinal tract resulting in a sensation of pseudo-fullness, physiological stress, changes in diet, growth inhibition, and decreased fertility (Isma and Danira, 2022). Microplastics may also serve as conduits for the introduction of bacteria into the water. Lower trophic levels are thought to acquire microplastics that have polluted the biota at higher trophic levels. The entry of microplastics into the bodies of biota can damage the digestive tract, reduce growth rate, inhibit enzyme production, reduce steroid hormone levels, and affect reproduction. Biota consume organisms at lower trophic levels and then experience biomagnification, in which case the biota also has the potential to be consumed by organisms at higher trophic levels, including humans, and affect the organisms' health (Wright and Kelly, 2017). Several emerging technologies can be employed as a means to deal with microplastics. One of such technologies is biorefinery, which can be implemented at or near a landfill, on the condition that plastic waste is separated from other kinds of waste. It will help reduce plastic waste on site and indirectly reduce waste as a whole (Madadian *et al.*, 2020).

Risk management

Risk management aims to control factors and risks that can cause health problems due to consuming refilled drinking water containing polyethylene terephthalate microplastics. In the risk analysis with an agent-oriented approach, several variables are measured to determine the magnitude of the risk, namely, the concentration of polyethylene terephthalate microplastics in the environment, duration of exposure, rate of intake, and frequency of exposure.

a. Risk control through the reduction of microplastics in drinking water can be performed by calculating the concentration at which polyethylene terephthalate microplastics in drinking water are safe for everyday consumption or use for a certain period of time.

b. Intake control can be performed by reducing the amount of consumption of refilled drinking water while maintaining other factors such as body weight, concentration of microplastics (polyethylene terephthalate), and frequency of exposure. Various efforts have also been made to degrade hazardous synthetic plastic polymers, which are currently the biggest contributor to plastic waste burden to the environment. Enzymes from actinomycetes, bacteria, fungi, insects, and other microbes have been researched for their possible involvement in the biodeterioration, biofragmentation, absorption, and mineralization of these petrochemical-based polymers and their minute components (Amobonye *et al.,* 2020). Other mitigation strategies focus on lowering plastic trash output and keeping it out of as many different habitats as feasible. It can be achieved using various procedures. Among those procedures are government initiatives to progressively or outright prohibit the widespread sale and usage of plastic bags as well as the commercial usage of microplastics in beauty products. Single-use plastic bag bans or/and restrictions are examples of such a strategy (Ogunola *et al.*, 2018).

Limitations

This study was limited to microplastics of the polyethylene terephalate polymer type. In addition, this study did not examine the stool of the respondents, so at what concentration polyethylene terephthalate microplastics are excreted from the human body stool is not known. Future researchers are suggested to develop other research regarding microplastics in drinking water. Monte Carlo simulations may also be implemented to determine the variables or values that have the most effect on exposure to microplastics in refilled drinking water.

CONCLUSION

Microplastic pollution has a far and wide presence in the environment. It can be encountered in the sea, sewage, clean water, food, air, water sources, and even in drinking water, including refilled drinking water. Microplastics of the polyethylene terepthalate type are mostly used for food and beverage packaging purposes. Microplastic particles of this type can translocate to the liver or spleen through the lymph, posing a risk of inflammation and changes in immune processes. Polyethylene terephthalate microplastic exposure in refilled drinking water in Tamangapa, Makassar City poses a health risk. Some measures of risk management that can be taken are to reduce the concentration of risk agents if the pattern and timing of consumption cannot be changed, reduce the consumption pattern (intake rate) if the concentration of risk agents and the time of consumption cannot be changed, and reduce contact time if the risk agent concentration and consumption pattern cannot be changed. Other mitigation strategies focus on lowering plastic trash output and keeping it out of as many different habitats as feasible. It can be achieved using various procedures. Among those procedures are government initiatives to progressively or outright prohibit the widespread sale and usage of plastic bags as well as the commercial usage of microplastics in beauty products. Single-use plastic bag bans or/and restrictions are examples of such a strategy. The limitation of this study lies in the use of only microplastics of the polyethylene terephalate type. The study also only discusses the effects on the human body through feces and without tracing deeper other health problems or health symptoms caused by exposure to microplastics (polyethylene terephthalate). Drinking water is safe for health if it meets the physical, microbiological, chemical, and radioactive requirements as mandatory parameters and additional parameters based on the Regulation of the Minister of Health regarding drinking water requirements.

AUTHOR CONTRIBUTIONS

S. Kasim dealt with the literature review, experimental design, methodology, analysis and interpretation of results, and preparation of the manuscript text and manuscript edition. A. Daud carried out the experiments, literature review, simulation modeling, data collection, and article writing. A.B. Birawida provided assistance with the literature review, data collection, and manuscript writing. Some of the final tests were carried out by A. Mallongi, who also oversaw data curation and validation. A.I. Arundhana read the manuscript and explained the model simulation's findings. A. Rasul compiled data and reviewed the presentation draft. M. Hatta assisted in the development of the manuscript and literature review.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS	DEFINITION
%	Percent
µm	Micrometer
ARKL	Environmental health risk analysis
C	Concentration
Cm	Centimeter
Dt	Duration exposure
fE	Frequency exposure
FTIR	Fourier transform Infra-red
Fig.	Figure
GCMS	Cromatografi gas spectrometri massa
HDPE	High density polyethylene
I	Intake
IR	Infrared
Km^2	Square kilometer
L	Liter
LPDE	Low density polyethylene
m	Meters
Max	Maximal value
Mg/kg/d	Milligram per kilogram per day
Min	Minimal value
MT	Million ton
nm	Nanometer
mm	Millimeter
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene

PS	Polystirene
PVC	Polyvinyl chloride
R	Rate
RfD	References doses
SEM	Scanning electron microscopy
Tavg	Average time period
USDFA	Us food and drug administration's
Wb	Weight of body

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ORIGINAL RESEARCH PAPER

The role of pro-environmental behavior in the development of sustainable tourism

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ABSTRACT

BACKGROUND AND OBJECTIVES: Sustainable tourism is tourism development that has a long-term impact on the environment, society, culture, and the economy for the present and the future. The benefits are felt by local people and tourists. The achievement of this research is the implementation of pro-environmental behavior, which is supported by tourist satisfaction and electronic word of mouth toward sustainable tourism as a form of environmental management policy in West Sumatra. This research aims to show three direct effects: first, the effect of satisfaction and electronic word of mouth on the sustainability of tourism; second, the effect of satisfaction on electronic word of mouth; and third, three moderating effects of pro-environmental behavior, namely, moderating the influence of tourist satisfaction on tourism sustainability, moderating the influence of electronic word of mouth on tourism sustainability, and moderating the influence of satisfaction with electronic word of mouth.

METHODS: This study is a quantitative study involving 420 tourists as respondents who visited West Sumatra from January to April 2023. Data analysis used partial least square–structural equation modeling. Structural equation modeling is a field of statistical study that can test a series of relationships that are relatively difficult to measure simultaneously. Partial least square is a component or variant-based structural equation model.

FINDINGS: After analyzing the data, it was determined that of the six hypotheses proposed in this study, five were accepted and one was rejected. The rejected hypothesis states that with a significance level of 0.199 > 0.05, pro-environmental behavior does not moderate the effect of electronic word of mouth on the sustainability of tourism. These findings clarify that the impact of electronic word of mouth on the sustainability of tourism is not mitigated by pro-environmental conduct.

CONCLUSION: When implementing sustainable tourism, not only economic factors are taken into account but also the preservation of nature and culture. Therefore, the stability of tourism in the future can be guaranteed without adversely impacting the environment.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
52	1	5

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INTRODUCTION

Currently, sustainable tourism (ST) plays a crucial role in the development of the tourism sector, as shown by various studies (Graci and Vilet, 2020; Weng *et al.*, 2021). More specifically, over the last 2 years, 1,175 article publications on this topic have been found via ScienceDirect, in terms of subject areas such as business, management, and accounting. Some regions in the world have begun taking this concept seriously, for example, Boracay Island in the Philippines. In 2015, 80% of Palau's waters were declared "no exploitation" areas. Even sunscreen is prohibited for use in Palau waters starting in 2020. Besides Palau, Ljubljana (Slovenia) was recognized as one of the world's best cities because it excels in addressing over-tourism. In the interim, the best nature category was won by the Netherlands (Goeree-Overflakke, Schouwen Duiveland, Veere, and Westvoorne), the United States (Lake Tahoe), and Ecuador (Sani Isla). For the best ecotourism category, Guyana, Tmatboey (Cambodia), and Serra Gorda (Mexico) won. In the category of best ST destinations on each continent, Tanzania (Chumbe Island), Ecuador (Galapagos National Park), Nepal (Bardia National Park), and Portugal (Agueda, Oeste-Region, Azores, Cascais, Lagos, Sintra, Torres Vedras, and Alto Minho CIM) became the best for their respective continents. Previous studies confirmed the benefits of ST for the economic and environmental sectors (Graci and Van, 2020; Luo, 2018; Man *et al.*, 2021; Park *et al.*, 2022; Wang, 2022; Weng *et al.*, 2021), making these an important issue that attracted the attention of researchers. The State of Global Islamic Economy (SGIE) report showed that problems in the tourism sector began to manifest in 2020 because of the impact of the COVID-19 pandemic, during which the decline has reached 70% (Elshaer *et al.*, 2021; Part *et al.*, 2022). Nevertheless, in 2021, this downturn will begin to emerge owing to the role of Muslim consumption for halal tourism, which saw an increase of 44 billion United States dollars (USD). Then, in 2022, SGIE also predicted that Muslim consumption for halal tourism will increase again up to 52 billion USD (Baba-Nalikant *et al.*, 2023). Moreover, the SGIE results are strengthened by the Global Muslim Travel Index (GMTI) analysis that in 2022, globally, Muslim tourist visits will continue to increase (Hwang *et al.*, 2023; Irawan *et al.*, 2022). In fact, GMTI has predicted that Muslim tourist visits in 2028 will reach 230 million with a consumption value of 225 billion USD (Sheasby, 2022). In addition, the 2022 GMTI also assessed Indonesia's advantages in the tourism sector, which includes excellence in the service and communication aspects, especially in West Sumatra (WS). Natural conditions and community culture are the keys to ST in WS. It has been proven that an increase in tourist visits to WS reached 5,100 in 2023 when compared to that in the previous year (Azizah, 2023; Scheyvens, 2021). This increase is mainly due to the natural beauty of WS, which is maintained because tourists understand pro-environment behavior (PEB) (Bilynets and Knezevic, 2022; Nowacky and Kowalczyk, 2023; Triši, 2023), which is necessary for achieving environmentally friendly tourism that focuses on environmentally responsible management practices, preserving biodiversity, involving and empowering local communities, and generating sustainable economic benefits for destinations and their residents. Investigations from previous research confirm that PEB can be obtained through motivation, socialization and the provision of infrastructure to reduce the impact of environmental degradation due to tourism (Bilynets and Knezevic, 2022; Park *et al.*, 2022; Preko *et al.*, 2019). Furthermore, other factors that influence ST in this study are tourist satisfaction (TS) and electronic word of mouth (EWOM) (Gerdt *et al.*, 2019; Lee *et al.*, 2020). TS is related to the response felt by tourists after making a tourist visit, which is assessed by their opinion about each destination's quality and performance (Setiawan, 2018; Surya *et al.*, 2018). Then, EWOM is closely related to digital marketing to create word of mouth using photos or videos as a form of electronic marketing (Gerdt *et al.*, 2019; Vema and Yadav, 2021). Although study regarding the relationship between the variables described previously has been researched previously, there is still a gap that can be developed. This study aims to analyze the determinants of ST, which comprise the direct influence of TS and EWOM. Meanwhile, PEB is positioned to moderate TS against ST, TS against EWOM, and EWOM against ST because PEB can strengthen and weaken the relationship between TS, EWOM, and ST. This study was conducted in West Sumatra, Indonesia, from January to April 2023.

MATERIALS AND METHODS

Sample selection

This study uses a quantitative approach. The population in this study were tourists visiting WS from January to April 2023. The study was conducted by

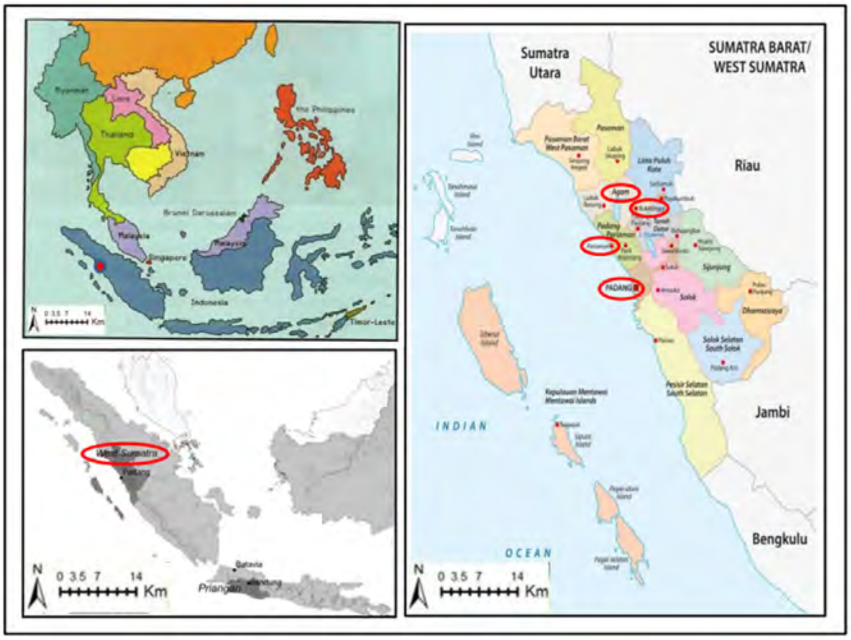

Fig. 1: Geographic location of the study area in the tourists visiting the cities of Padang, Pariaman, Agam, and Bukittinggi in Indonesia

distributing questionnaires to tourists visiting the cities of Padang, Pariaman, Agam, and Bukittinggi, where the geographic location of the study area is shown in Fig. 1.

Fig. 1 informs the location of the WS geographically, that is, on the line 00 54' North Latitude to 30 30' South Latitude and 980 36' to 1010 53' East Longitude with a total area of around 42,297.30 km^2 or 4,229,730 Ha including ±391 large and small islands in the vicinity. Then, the WS climate is generally tropical with quite high air temperatures, that is, between 22.6°C and 31.5°C. This province is also crossed by the equator, precisely in Bonjol, Pasaman. Furthermore, this study uses a side accidental technique, where samples are taken randomly, without prior planning. Moreover, this study uses the hair formula that the number of representative samples depends on the number of indicators multiplied by 5 to 25 (Tejada and Punzalan, 2012). Based on this explanation, this study uses 20 indicators multiplied by 21, so the number of samples used is 420, which is shown in Table 1.

This study uses grouping characteristics of respondents based on age, occupation, and income. This is accomplished because of various tourists, so grouping the characteristics of the respondents, the interest of certain groups in visiting tourist destinations (TDs) in WS can be known. Based on the tourist age group, it was dominated by tourists aged 18–30 years by 53%. Based on the work of tourists, the number is almost average between students, private employees, and government employees. Based on tourist income, it is dominated by tourists with an income of 65–650 USD by 51%.

Variable measurement

This study uses a Likert scale questionnaire to measure the respondent's level of agreement or disagreement with certain statements. All variables in this study were measured using a Likert scale (ranging from 1 = strongly disagree to 5 = strongly agree). This study comprises four variables. ST consists of five indicators, and TS consists of five indicators. The EWOM comprises five indicators. The PEB consists of five indicators. The total indicators used in this study were 420 respondents, as shown in Table 2.

Data analysis

The data is analyzed using the partial least square–structural equation modeling (PLS-SEM). PLS-SEM investigates the relationship between unobserved or latent variables in a relatively complex research model with exogenous/independent, moderating, and endogenous/dependent variables. Using PLS, simultaneous hypothesis testing results can be obtained by minimizing measurement and

Table 1: Profile of respondents

Characteristics	Items	Achievement	
		Frequency	%
Age	18–30 years old	221	53
	31–40 years old	89	21
	More than 40 years old	110	26
Occupation	Student	151	36
	Private Company Worker	149	35
	Civil Servant	120	29
Income	65–650 USD	216	51
	Between 651 and 1,300 USD	98	23
	More than 1,300 USD	106	25

Table 2: Research IndicatorsTable 2: Research Indicators

Indicators	Measurement items	Sources
ST	5	Elshaer *et al.*, 2021
		Sobaih *et al.*, 2021
TS	5	Marques *et al.*, 2021
		Milman *et al.*, 2020
		Shayk-Baygloo, 2022
EWOM	5	Semrad and Rivera, 2016
PEB	5	Bilynets and Knezevic, 2022

structural errors. PLS-SEM analysis was conducted in accordance with the recommendations in two stages: 1) evaluation of the measurement model (outer model that explains the relationship between latent variables and their indicators and 2) evaluation of the structural model or inner model that explains the relationship between latent variables/constructs. This study investigates the relationship between the effects of ST, TS, EWOM, and PEB shown in Fig. 2.

TS has an effect on ST in West Sumatra Tourist Destinations (WSTD)

Public interest and strategies to promote ST can be assessed from TS, which include the increase in tourists' mental health through the happiness they feel after a tourist visit (Chai *et al.,* 2021; Gryshchenko *et al.,* 2022). Then, the implementation of ST aims to fulfill the expectations of TS who are satisfied with TD because they do not want TD to become extinct (Chai *et al.,* 2021; Song *et al.,* 2019). This is due to the possibility of return visits by tourists to the TD, where TS will contribute to ST (Khan *et al.,* 2022).

H1: TS has a significant effect on ST in WSTD

TS has an effect on EWOM in WSTD

Several factors influence EWOM, including TS and consumer experience (Akinci and Aksoy 2019; El-Manstrly *et al.,* 2021). Conversely, many previous studies also reveal that TS has an impact on behavior, which is closely related to EWOM for decision making (Campón-Cerro *et al.,* 2017; Chao *et al.,* 2021). In addition, perceived dissatisfaction and satisfaction can be an informal source of information because those who are satisfied will give positive EWOM reviews, so they will become loyal customers (Chen *et al.,* 2018; Yan *et al.,* 2018).

H2: TS has a significant effect on EWOM in WSTD

EWOM has an effect on ST in WSTD

EWOM informs positive or negative statements posted by visitors, so this marketing model has a challenge (Yan *et al.,* 2018; Yen and Tang 2019). EWOM is related to TS, which they will convey on social media to share information with the wider community who will travel so that it will influence a person's intention to travel (Gerdt *et al.,* 2019). Moreover, TS and ST have involved user-generated content as a data source for exchanging information between tourists through EWOM (Yan *et al.,* 2018).

H3: EWOM has a significant effect on ST in WSTD

PEB moderates the effect of TS on ST in WSTD

PEB reflects actions to manage behavior that reduces the physical and nonphysical carrying capacity of the environment (Berthold *et al.,* 2022; Top and

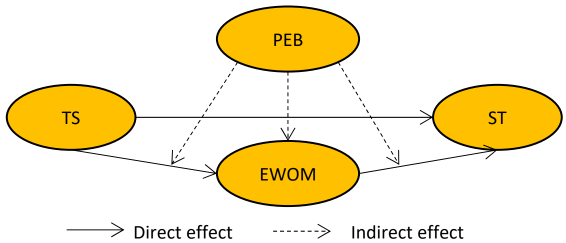

Fig. 2: Measurement model

Speekenbrink, 2022; Wyss *et al.,* 2022). Behind the various benefits of the tourism sector, it turns out that the number of visitors and increasing infrastructure in the tourism sector have a bad effect on the carrying capacity of the environment because it will produce waste such as rubbish (Koller *et al.,* 2023; Cuong *et al.,* 2022; Juniardi *et al.,* 2022). The aesthetics of DT will be disturbed if waste management is not carried out well, which in the long term will weaken EWOM for ST (Bilynets and Knezevic, 2022).

H4: PEB significantly moderates the effect of TS on ST in WSTD

PEB moderates the effect of EWOM on ST in WSTD

Waste in the form of garbage is a negative externality from the tourism sector to the environment because it will trigger environmental degradation due to the flow of waste generation (Bilynets and Knezevic, 2022; Ehzari *et al.,* 2022; Nowacky and Kowalczyk-aniol, 2021; Samimi *et al.,* 2023). The waste problem is caused by domestic and foreign tourists, where a 1% increase in tourist visits will result in an increase in the quantity of waste by 1.25% and an increase in waste generation by 0.51% (Rakotoarisoa, 2020). One action to reduce this problem is to enforce PEB through reviews posted on social media, namely, EWOM.

H5: PEB significantly moderates the effect of EWOM on ST in WSTD

PEB moderates the effect of TS on EWOM in WSTD

PEB can work in two ways, that is, it can strengthen and weaken TS and EWOM toward ST (Akinci and Aksoy, 2019). The sustainability of ST cannot be separated from the behavior of tourists who maintain the carrying capacity of the environment when they enjoy DT (Chao *et al.,* 2021). Contrasting conditions for tourists who do not maintain the environmental carrying capacity will hinder the sustainability of ST (Gerdt *et al.,* 2019). Then, TS will be achieved if the services provided by DT match or exceed their expectations (Lee *et al.,* 2020; Stanton *et al.,* 2019). Additionally, EWOM contributes to creating subjective and objective reviews online to assist potential tourists in making visiting decisions (Quan *et al.,* 2021).

H6: PEB significantly moderates the effect of TS on EWOM in WSTD

RESULTS AND DISCUSSION

Evaluation of measurement and structural models

The first stage in the PLS-SEM analysis evaluates the measurement model to meet the reliability and construct validity criteria. The results in Table 3 show that the composite reliability (CR) values and Cronbach's alpha (CA) are within the acceptable range of the construct reliability standard, which is more than 0.70. The convergent validity standard for all individual items is within the acceptable loading factor (LF) criteria, which are more than 0.70 and are statistically significant (probability [p] values of <0.01). Similarly, the average variance extracted (AVE) values are more than 0.50, which indicates acceptable convergent validity. Discriminant validity (DV) was evaluated by comparing the square root of AVE with correlations between the constructs. The results in Table 3 indicate that the square root of AVE in the diagonal column is higher than the correlation between the constructs (the numbers in the same column), which shows that the discriminant validity criteria are met.

The results in Table 4 show the DV, in which two conceptually different concepts must show sufficient differences. The point is that a set of indicators that are combined are expected not to be unidimensional. DV refers to the degree to which certain constructs within the same model differ from one another. There are three types of analysis used to test DV, namely, Fornell and Larcker criteria, cross-loadings, and heterotrait–monotrait ratio (HTMT). HTMT analysis has been proven to be superior among other methods for

Table 3: Loading factor, composite reliability, average variance extracted, and Cronbach's alpha

Indicators	LF	CR	AVE	CA
ST		0.900	0.648	0.859
It is supported by ST on WS	0.579			
It participates in ST	0.798			
It complies with the regulations in force in WS to reduce the negative impacts of tourism	0.818			
It cooperates in planning efforts and ST	0.776			
It participates in the promotion, education, and conservation of the natural environment in WS	0.789			
TS		0.830	0.497	0.748
The visit overall was satisfactory	0.638			
Overall a pleasant visit	0.623			
The work-holiday experience at the destination was overall pleasant	0.774			
Involvement in working holiday tourism at the destination as a whole is enjoyed	0.756			
Working holiday travel to these destinations is a wise decision	0.720			
EWOM		0.886	0.556	0.845
Positive photos about WS will be posted	0.763			
Positive comments about WS will be provided	0.713			
Positive videos about WS will be posted	0.796			
Positive tweet posts about WS will be posted	0.769			
Family and friends will be tagged and mentioned when sharing experiences on social media	0.668			
PEB		0.900	0.648	0.859
Straws/bags/cups are used once at the destination	0.832			
Plastic bottles are placed in recycling bins at their destination	0.853			
Tumblers and lunch boxes are taken when traveling	0.839			
Trash is put in bags when the trash can is not visible	0.873			
Save water when bathing and performing ablution	0.593			

assessing discriminant validity because all HTMT ratios obtained are lower than the maximum threshold of 0.85. Thus, this study uses HTMT analysis in assessing DV.

Hypotheses testing results

The results in Table 5 show the hypothesized findings. The analysis results show the following: First, TS influences ST, which means that increasing TS will also encourage ST. Second, EWOM influences ST, which means that increasing EWOM will also encourage an increase in ST. Third, TS influences EWOM, which means that increasing TS will also encourage an increase in EWOM. Fourth, PEB moderates the influence of TS on ST, which means that PEB strengthens the influence of TS on ST. Fifth, PEB does not moderate the influence of EWOM on ST, which means that PEB weakens the influence of TS on ST. Sixth, PEB moderates the influence of TS on EWOM, which means that PEB strengthens the influence of TS on EWOM. ST is determined by its ability to adapt to tourist and TS conditions to fulfill these two things requires an innovative strategy (Preko *et al.,* 2019). ST cannot be separated from the role of technology and innovation in the tourism sector, which can be grouped into three types. First, tourism planning can be conducted using online reservations, which includes most reservations for plane tickets and accommodation using online reservations. The presence of online reservation supporting applications makes ordering easier so it is very popular with people in this digital era. Second, on the road like a mobile phone is the best guide for traveling. A traveler can get various information just by using a smartphone, starting from the tourist attractions to visit, how to get there,

Table 4: Result of discriminant validity

	R	STD	TS	Z1	Z2	Z3	EWOM
R-square (*R*)	0.805						
Standard deviation (STD)	0.708	0.757					
TS	0.732	0.813	0.705				
Z1	0.470	0.114	0.178	1.000			
Z2	0.343	0.028	0.065	0.786	1.000		
Z3	0.470	0.114	0.178	1.000	0.786	1.000	
EWOM	0.618	0.814	0.773	0.059	-0.083	0.059	0.752

Table 5: Results of hypothesis

H	Hypotheses	Coefficient	*T*-values	Significant	Decision
H1	TS has a significant effect on ST in WSTD	0.318	5.204	0.000	Accepted
H2	TS has a significant effect on EWOM in WSTD	0.424	7.509	0.000	Accepted
H3	EWOM has a significant effect on ST in WSTD	0.633	12.281	0.000	Accepted
H4	PEB significantly moderates the effect of TS on ST in WSTD	0.147	3.035	0.003	Accepted
H5	PEB significantly moderates the effect of EWOM on ST in TD	0.073	1.286	0.199	Rejected
H6	PEB significantly moderates the effect of TS on EWOM in WSTD	0.177	4.148	0.000	Accepted

and places to eat typical of a region to places to shop for souvenirs. Third, post-trip, which includes sharing, going live, or posting activities, has become a daily habit for people, including when we are on a tourist trip. Additionally, ST must be integrated in three dimensions, namely, environmental, economic, and social. Based on the context of sustainable development, ST can be defined as tourism development that suits the needs of tourists while still paying attention to sustainability (conservation, environmental dimensions), providing opportunities for the younger generation to utilize (economic dimensions), and developing them based on the social order (social dimensions) that have been established.

ST must be more comprehensive in improving TS through support from improving the quality of infrastructure, as well as social and community improvements (Luo, 2018). ST research has been concerned with predicting such behavior. Sustainability is influenced by TS (Cai *et al.,* 2021). TS plays an important role in attracting public interest and strategies to promote ST (Cai *et al.,* 2021). The results of the study show that the positive atmosphere and quality attributes of the sustainability of a destination increase the happiness and satisfaction of tourists and improve their mental health so that it has a significant impact (Cai *et al.,* 2021; Song *et al.*, 2019). Thus, ST is the hope of tourists who have been satisfied with the destination. Tourists do not want these destinations to become extinct. One day they might visit again if they are satisfied with the destination. This satisfaction will lead to loyalty. Therefore, it is suspected that ST affects tourist satisfaction and loyalty. For managers of TD, EWOM is valuable information. Loyal and trustworthy modern travelers usually like to share their experiences with others through reviews on the internet. EWOM is what helps attract friends, family, and other potential travelers. EWOM also serves as a guide for others. The point is to influence consumer decision making, product evaluation, and purchase intentions (Correia and Ferreira, 2020). Research (Correia and Ferreira, 2020) also explains that EWOM has an important role in the sustainability of tourism and hospitality destinations. EWOM is considered the most powerful form of advertising because consumers trust their friends 92% more than traditional media. Traditional marketing often comes in the form of paid advertising. These are often referred to as drivers of marketing activities. In contrast, EWOM marketing focuses on user-generated content to market brands (Bartschat *et al.,* 2022). In this study, it was revealed that the encouragement felt by customers will affect their intention to try. This will then make customers loyal to a product/brand. Therefore EWOM is proven to affect ST. Several factors influence EWOM, including customer satisfaction and experience, store decoration, and quality of service personnel. All aspects related to the restaurant brand can be considered as reference items (Chao *et al.,* 2021). Empirical research in this literature strengthens previous research on the relationship between satisfaction and EWOM. The results of the analysis that has been conducted show that there is a relationship between satisfaction and EWOM. This study finds that EWOM is promoted by consumers, has a greater impact, and is more effective than advertising. Furthermore, the results of the analysis show that satisfaction affects EWOM, in which the variable relationship is proven to be unidirectional. This finding means that the higher the TS value, the higher the EWOM. Conversely, the lower the TS value, the lower the EWOM. ST and EWOM are very important things in the tourism industry, so tourists' needs must be met so that they are satisfied with what they want. Positive environmentally friendly behavior keeps TD clean and comfortable. However, there are also tourist behaviors that have a negative impact on TD, for example, the waste generated and damage to facilities. Scattered trash disrupts the comfort of TD. More broadly, waste creates odors and spreads disease. This condition is certainly avoided by tourists. Widespread environmental pollution will, of course, weaken the link between eWoM and tourism sustainability (Bilynets and Knezevic, 2022). Research on PEB behavior has a strong potential to reduce environmental impacts. Appeals and invitations for TD managers to tourists to protect the environment will have an impact on the comfort of the tourists themselves. If tourists feel comfortable with travel, they will provide reviews of what they feel. Nowadays, tourists love to leave online reviews on their social media. This review will later be seen and read by internet users around the world so that it can be interpreted that tourists' eco-friendly behavior can strengthen the influence between EWOM and ST (Park *et al.*, 2022). PEB is a factor that can strengthen and weaken TS and EWOM against ST (Gerdt *et al.,* 2019). The challenges and obstacles faced in promoting and implementing PEB in the tourism industry are that ST must be able to pay attention to agreements, regulations, and laws at both national and international levels so that it can run smoothly without obstacles. And also form cooperation with local communities to monitor and prevent violations of applicable regulations. Apart from that, ST must be able to guarantee sustainability, provide benefits to current society, and not harm future generations. This is because the assumption that tourism development has the potential to damage the environment is logical if it is linked to the increase in the number of tourists and the degradation of the tourism destination area. PEB that influences ST can guarantee sustainability, providing benefits to current society and not harming future generations. This is because the assumption that tourism development has the potential to damage the environment is logical if it is linked to the increase in the number of tourists and the degradation of the tourism destination area. Then, tourism must grow based on the principle of optimization, not exploitation. Apart from that, there must be periodic monitoring and evaluation to ensure that tourism development continues to run within the concept of sustainable development, using the principles of capacity management, both regional capacity, capacity of certain tourist attractions, economic capacity, social capacity, and other resource capacities so that ST can continue. Environmental sustainability and environmental comfort created through eco-friendly behavior from tourists strengthen ST. Conversely, tourists who are not aware of the importance of protecting the environment will weaken ST. TS has a role in building an impression on tourists. A sense of joy and happiness makes tourists willing to help tour managers develop these TDs. This means that the tourist manager's call to protect the environment will be obeyed by tourists. Thus, compliance with protecting and maintaining the environment, which is reflected in environmentally friendly behavior will strengthen the influence between TS on ST (Rakotoarisoa, 2020).

CONCLUSION

The main finding of this study is that TS and EWOM have a significant effect on ST in WSTD, respectively, 0.318% and 0.633%. TS has a significant effect on EWOM in WSTD of 0.424%. PEB significantly moderates the effect of TS on ST at 0.147% and TS on EWOM in WSTD at 0.177%. The results of the direct effect study show that TS and EWOM affect ST. This finding reinforces that if TS goes with their tour it will guarantee ST. Similarly, if tourists often make positive reviews on their social media, these TDs will become more famous and crowded. This condition will make these TDs able to improve their performance. Improving the performance of TD guarantees ST. Then, TS influences EWOM. The pleasant impression experienced by tourists makes them provide positive reviews and testimonials on their social media accounts. Educational program strategy in encouraging PEB among tourists and tourism stakeholders through outreach activities to reach ST. Environmental education provides visitors with important knowledge about the natural environment and sustainability. Through educational programs, visitors can learn about local ecosystems, biodiversity, and environmental challenges facing tourist destinations. This information helps visitors understand how important it is to protect and preserve the environment they visit and the positive impact they can have through appropriate actions. Apart from knowledge, environmental education also helps change the mindset and behavior of visitors. By understanding the negative impacts that irresponsible actions can cause, visitors will be more likely to adopt sustainable practices when traveling. They will reduce waste, use natural resources wisely, and respect local flora and fauna. In this case, environmental education acts as a trigger for sustainable behavior change. Furthermore, environmental education helps build awareness of the importance of visitor involvement in environmental conservation efforts. Visitors can learn about existing conservation programs and initiatives in tourist destinations, as well as how they can contribute and help in maintaining sustainability. By understanding that they have an important role in environmental conservation, visitors will feel involved and committed to contributing to conservation efforts. Moreover, environmental education can be provided via various communication channels, such as information signs, guides, brochures, or educational tours. Tourists are also urged to maintain the beauty of nature by not destroying the beauty of natural sites with graffiti and pictures. Preserving the natural surroundings is also one of the efforts to assist the development of ST. Based on the conclusions of the study results, community participation should be the basis for ST WSTD. If the government carries out ST in WS, it must partner with the community through social roles, cultural roles, economic roles, trust, networks, and norms, which are the pillars of tourist attractions in WS, which are embodied in Sapta Pesona. The role of the private sector must be further optimized in promoting tourism in WA through print or electronic media and organizing tourism events. The private sector partners with communities around tourist destinations in building accessibility and collaborating with the government and related stakeholders, in the field of human resource development. Tourism developed in WA must maintain social capital in the form of cultural values, customs, and norms that apply in society so that local culture is not damaged or displaced due to tourism development. The diverse cultures and customs must be developed to become a tourist attraction. Local community participation in ST must be further increased by strengthening organizations in the tourism sector, such as forming culinary and souvenir groups, which are the main source of livelihood for the WS community. Furthermore, the WA government must pay attention to three main components to achieve ST in WSTD, namely, environmentally sustainable, economically sustainable, and socioculturally sustainable. Environmental sustainability is carried out through the optimal use of environmental resources by limiting resources, maintaining ecological processes, and maintaining the sustainability and existence of natural heritage and biodiversity in tourist destinations. Economic sustainability is carried out by reducing poverty levels, encouraging economic growth, and creating jobs. Meanwhile, sociocultural sustainability is carried out by maintaining the sociocultural authenticity of local communities with mutually agreed rules and regulations, preserving local cultural heritage and customary values, and increasing intercultural tolerance and understanding. Apart from that, encouraging ST in WS requires an integrated plan involving various sectors and various stakeholders. In tourism development, four things must be fulfilled, namely, attractions, accessibility, amenities, and ancillary services, the fulfillment of which involves various sectors and stakeholders. This integrated planning contains spatial planning, which must be according to the regional spatial plan; calculation of carrying capacity, such as ecological carrying capacity, physical carrying capacity, and social carrying capacity; environmental impact analysis studies or environmental management efforts; environmental monitoring efforts; environmentally friendly use of natural resources; and the roles and responsibilities of each stakeholder. Based on the limitations of this study, ST also must be developed apart from the variables that have been studied in this study (TS and EWOM). Other factors can affect ST, including tourist experience and traveling benefits. This study has also analyzed the direct effect. The next researcher is expected to continue research by investigating the effect of mediation. This study has only shown PEB as a moderating variable; future researchers are expected to add other variables such as travel benefits, tourist well-being, and self-control. Future trends and emerging research directions in the field of ST concerning PEB behavior seek to realize three qualities, namely, tourism must be able to realize the quality of life of local communities, tourism must be able to provide quality effort to service providers in the tourism industry, and the next and most important thing is to create a quality tourist experience.

AUTHOR CONTRIBUTIONS

N. Zulvianti, the corresponding author, has contributed to preparing all the tables and figures and interpretation of the results and participated in the interpretation of the PLS-SEM results and manuscript preparation. H. Akmal, the second author, has contributed to preparing all the tables and figures and interpretation of the results and participated in the interpretation of the PLS-SEM results and manuscript preparation. M.R. Putra, the third author, has contributed to preparing all the tables and figures and interpretation of the results and participated in the interpretation of the PLS-SEM results and manuscript preparation.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest in terms of the publication of this manuscript. Moreover, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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ABBREVIATIONS

%	*Percent*
=	Similarity
()	Parenthesis
<	Less than
±	*More or less*
°C	*Degrees Celcius*
AVE	Average variance extracted
CA	Cronbach's alpha
CR	Composite reliability
DV	Discriminant validity
et al.	Et alia
EWOM	Electronic word of mouth
Fig.	Figure
GMTI	Global Muslim travel index
H	Hypothesis
H1	Hypothesis 1
H2	Hypothesis 2
H3	Hypothesis 3
H4	Hypothesis 4
H5	Hypothesis 5
H6	Hypothesis 6
Ha	Hectare
HTMT	Heterotrait–monotrait ratio
LF	Loading factor
P	Probability
PEB	Pro-environment behavior
PLS	Partial least square
R	*R*-square
SEM	Structural equation model
SGIE	State of global Islamic economy

ST	Sustainable tourism
STD	Standard deviation
TD	Tourist destinations
TS	Tourist satisfaction
T-value	or T-score ratio of the difference between the mean of the two sample sets
USD	United State dollars
WOM	Word of mouth
WS	West Sumatra
WSTD	West Sumatra tourist destinations
Z1	Moderation 1
Z2	Moderation 2
Z3	Moderation 3

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