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CASE STUDY

Life cycle assessment of biomass waste briquettes as renewable energy

M.N. Rashif[1], S. Hartini[1,2,*], D.P. Sari[1,2], B.S. Ramadan[3], T. Matsumoto[4], A.T. Balasbaneh[5]

[1] *Department of Industrial Engineering, Faculty of Engineering, Universitas Diponegoro, Prof. Sudarto S.H., Tembalang, Semarang, Indonesia*

[2] *Lean and Sustainable Supply Chain Laboratory, Department of Industrial Engineering, Faculty of Engineering, Universitas Diponegoro, Indonesia*

[3] *Environmental Sustainability Research Group, Department of Environmental Engineering, Faculty of Engineering, Universitas Diponegoro, Jl. Prof. Sudarto S.H., Tembalang, Semarang City, Central Java 50275, Indonesia*

[4] *Institute of Environmental Science and Technology, The University of Kitakyushu, 1-1, Hibikino, Wakamatsu-ku, Kitakyushu, Fukuoka, 808-0135, Japan*

[5] *LSBU Business School, London South Bank University, 103 Borough Road, London SE1 0AA, United Kingdom*

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ABSTRACT

BACKGROUND AND OBJECTIVES: A significant amount of biomass waste remains underutilized in corn and rice farming areas. In Grobogan, Central Java, rice husks, and corn waste are used as energy sources for tofu production, resulting in the formation of rice husk charcoal and corncob charcoal. Consequently, it is essential to develop innovative methods for converting rice husks and burnt cob waste into products of economic value. This study sought to ascertain the ideal mixture of briquettes derived from biomass waste, particularly corncobs, burnt corncobs, burnt rice husks, and polypropylene waste, by analyzing their chemical characteristics and the associated environmental effects.
METHODS: This experimental design was selected to determine the optimal combination of materials for producing high-quality briquettes. In this design, the combination of materials was the independent variable, whereas the chemical characteristics were the dependent variables. The dependent variables selected for this study were derived from the parameters specified by the Indonesian National Standards, which included measurements of water content, calorific value, ash content, and fixed carbon. A life cycle assessment was performed to evaluate the environmental impact of the briquette products manufactured.
FINDINGS: The results of the study showed that corn cob briquettes exhibited better quality than burnt rice husk briquettes based on the Indonesian National Standard parameters. A life cycle assessment pertaining to recycling demonstrated that corn cob briquettes possess a lesser environmental impact. The study indicated that corn cob briquettes, when produced without the inclusion of plastic, exhibited superior chemical properties and a more favorable environmental impact. Corncob without polypropylene had a moisture content of 11.16 percent, ash content of 20.04 percent, fixed carbon content of 77.44 percent, and calorific value of 5,156.93 calories per gram. The environmental impact is equivalent to an eco-cost of 0.387 United States Dollars The findings of the study reveal that corn cob briquettes hold substantial potential for evolution as an alternative energy resource or for integration with fossil fuels in co-firing processes.
CONCLUSION: The findings will assist local governments in guiding the production of biomass briquettes that meet consumer quality standards, while minimizing environmental impact. There is a necessity for further studies to analyze the impediments and challenges involved in the utilization of briquettes as a replacement for fossil energy or in conjunction with fossil fuels in industrial applications, especially within the cement industry in Grobogan Regency.

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51	4	7

*Corresponding Author:
Email: *srihartini@lecturer.undip.ac.id*
Phone: +62813 2760 9560
ORCID: 0000-0001-5659-6083

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INTRODUCTION

In the last decade, increasing the value of waste production and extending the use of resources has been increasingly recognized as a solution to the ecological and socioeconomic challenges arising from the growing consumption of non-renewable resources (Goyal et al., 2021). The notion of a circular economy (CE) advocates for the efficient and sustainable utilization of resources as a means to attain sustainable development (Aarikka-Stenroos et al., 2021). Processing waste into renewable energy from a circular economy perspective is crucial because it can mitigate climate crises (Akbari et al., 2021), produce renewable energy, and recover waste (Hartini et. al., 2024, thereby reducing dependence on natural resources and fossil fuels (Alonso-Almeida et al., 2021), promoting sustainability (Laureti et al., 2023), creating green jobs in industries such as recycling, repair, and product reuse (Batista et al., 2023), and increasing resource efficiency and economic benefits (García-Valderrama et al., 2024). A large volume of postharvest agricultural waste is not being fully utilized. Biomass waste can be converted into economically beneficial products like briquettes, which can act as a renewable energy alternative (Sanchez et al., 2022). Conversely, if this waste is not managed properly, it can have detrimental effects on the environment (Sanka et al., 2024). As renewable energy sources, briquettes provide a viable alternative to fossil fuels, including petroleum, which currently meets 80 percent of global energy demands but is encountering diminishing reserves (Kpalo et al., 2020). Briquettes are widely used as renewable energy sources to address the issue of excessive dependence on wood fuel (Olugbade et al., 2019). As a cost-efficient solution, biomass briquettes can play a crucial role in mitigating carbon dioxide (CO2) emissions (Morales-Máximo et al., 2022). This was confirmed by Sulaiman et al. (2020), who conducted a study in 27 European Union (EU) countries and showed that the use of biomass energy can reduce CO_2 emissions compared to fossil energy. Grobogan Regency is the largest producer of rice and corn in Central Java, Indonesia. As reported by the Central Statistics Agency in the 2021 census, Grobogan generates an estimated 800,000 tons of rice and 830,000 tons of corn. Agricultural activities in the region generate significant amounts of rice husk and corncob waste. Prior studies have demonstrated that agricultural byproducts such as rice husk and corncob possess the capability to be transformed into briquettes. Quality evaluations conducted on rice husk charcoal briquettes have determined that they are appropriate for use as clean energy sources and as fuel for domestic purposes (Kpalo et al., 2020). The study revealed that the combustion efficiency of rice husk briquettes increased by 20% as a result of the solid briquette formation.. Utilizing renewable energy from organic waste is a cost-effective technology that can reduce CO_2 emissions (Morales-Máximo et al., 2022). Studies conducted in Bangladesh suggest that transitioning from wood fuel to rice husk briquettes has the potential to preserve approximately 24.14 thousand hectares of forested land from deforestation annually (Ahiduzzaman and Islam, 2016). Similarly, Waheed et al. (2023) found that briquettes made from a mixture of corn waste were suitable for both household and industrial applications. This finding is supported by Ngubane and Oyekola (2023), who noted that corn waste is an ideal material for environmentally friendly solid fuels (briquettes) because of its high carbon content and calorific value. Extensive studies have been carried out on briquettes, with particular attention given to bioenergy and the techniques utilized in the conversion of biomass into briquette form. Current research mainly explore the relationship between different independent variables and the quality of briquettes produced from various types of raw materials. For example, studies have investigated the effect of biomass type on briquette quality (Stolarski et al. 2013). In addition to biomass type, the influence of several factors such as the dimensions of raw materials, moisture content, binding properties, and the techniques used in briquette manufacturing has been investigated in relation to briquette quality (Olugbade et al., 2019). A research has indicated that briquettes derived from rice husks possess a low bulk density, which adversely affects their durability. Therefore, managing the moisture content is crucial for enhancing the quality of these briquettes (Saeed et al., 2021). However, relatively few studies have examined the environmental impact of using biomass briquettes compared with fossil fuels (Saba et al., 2020). In addition to the by products of rice husks and corn cobs, the inhabitants of Grobogan are also responsible for the substantial generation of plastic waste. This plastic waste is detrimental to environmental health,

with research conducted by Sabilillah et al. (2023) revealing that microplastics lead to pollution in waterways and adversely impact fish species. The presence of microplastics poses a heightened risk to human health, particularly affecting the digestive system, as these particles traverse the food chain. There are many types of plastics that possess thermoplastic properties, including polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS). It is important to recognize that not all plastics are suitable for briquette production; some are safe, while others are not. Among them, PP plastic bags are particularly advantageous, as they have a melting point of approximately 160 degrees Celsius (°C). Furthermore, the calorific value associated with this plastic is greater than that of coal (Diningsih and Rangkuti, 2020). In the context of sustainable development, resource conservation, reuse, and recycling of waste are crucial for environmental protection. Waste reduction minimizes the amount of waste sent to landfills, reduces overall waste, and purifies raw materials such as iron waste (Ardelean *et al*., 2022), furniture (Hartini *et al*., 2022), wood waste (Wicaksono *et al*., 2020), and food waste (Slorach *et al*., 2020). Within the framework of a circular economy, effective waste management is crucial for enhancing the recycling and recovery processes of materials throughout their entire life cycle (Ferronato *et al*., 2022). Biomass waste can then be recycled into briquettes. Briquettes serve as renewable fuels, which is particularly important given that fossil fuels, such as petroleum products, coal, and natural gas, currently meet 80% of the global energy needs (Kpalo *et al*., 2020). Apart from coal, it is possible to create briquettes by blending coal with different materials. Investigations have indicated that when coal is mixed with lignocellulosic components, as well as a combination of charred coal, wood, and plastic, the resulting product is a high-quality fuel (Trihadiningrum *et al*., 2007). Grobogan Regency has more than 50 tofu production houses that require energy sources for cooking and frying processes. Around 30 are in Sugihmanik Tanggungharjo, while the others are spread across Getasrejo, Purwodadi, Tawangharjo and Toroh Villages. The consumption of firewood is a significant factor in deforestation, leading to a diminished availability of this resource. Consequently, tofu SMEs are seeking alternative options, such as utilizing rice husks, with some even experimenting with the use of discarded tires. Ash waste from burning rice husks and used tires easily flies, polluting the environment and causing air pollution. Many people complain and report to the Grobogan Environmental Service. In addition, rice husks that are easily scattered and burned are at high risk of fire. From 2022 to 2023, there were two fires in tofu SMEs owing to scattered rice husks. Briquettes are safe and cheap biofuels that can be produced from agricultural harvest residues in rural communities. Due to its simplicity and low cost, the production method is accessible, allowing small and medium-sized enterprises (SMEs) and marginalized rural communities to implement this idea (Meincken and Funk, 2014). Briquettes in solid form have better thermal and physical properties than the briquette materials from which they are derived. In agricultural-based countries with abundant biomass waste, these wastes can be effectively utilized through conversion into briquettes to achieve substantial improvements in energy utilization (Dinesha *et al*., 2019). Considering the issues outlined earlier, the hypothesis of this study asserts that there is an availability of biomass waste in the Grobogan Regency that can be effectively harnessed by SMEs and industries in the area, while adhering to the national standards set by Indonesia. Related to this, this study aims to identify the optimal combination of briquettes made from rice husks and corncobs by incorporating PP plastic as an independent variable. An experimental design will be employed to determine the best combination of rice husks and corn cobs when mixed with plastic, as well as when used without it. Prior studies have typically issued recommendations based on the quality of dependent variables evaluated through laboratory results. However, these studies have not undertaken thorough quality assessments of corn briquettes and burned rice husks, both in the presence of and absence of polypropylene. A review of the literature requires more updating with work to obtain a clear and concise state-of-the-art analysis. This ought to more explicitly delineate the identified knowledge deficiencies and associate them with the aims of the current study. While the general introduction is acceptable, the state-of-the-art review that follows is very difficult to understand and no specific thoughts can be inferred. One of the primary constraints of this

study is the absence of a well-defined debate or argument. The innovative aspect of this research is its use of life cycle assessment (LCA) to perform an environmental impact analysis of the proposed combinations. Consequently, recommendations will be based not only on laboratory test results but also on the environmental impact of the produced briquettes. This study focused on the reduction of biomass waste and its conversion into an eco-friendly alternative energy source. The methodology employed included an experimental design that integrated corncob waste and burnt rice husks with polypropylene waste to produce briquettes. Each experiment was subjected to environmental impact assessment. Briquettes with the best chemical characteristics and environmental impact are recommended for development. The study was conducted in Grobogan Regency, Central Java, Indonesia. This study was conducted from 2023 to 2024.

MATERIALS AND METHODS

Study area

For this study, the raw materials consisted of corn cobs collected from farming areas, along with burnt corn cobs and burnt husks acquired from the waste generated by the combustion processes of tofu SMEs located in Sugihmanik Village, Grobogan, Indonesia. The corresponding location map is illustrated in Fig. 1. This study explores the potential of using biomass waste as a raw material for briquettes, focusing on the Grobogan Regency. Grobogan is the second largest rice-producing region in Central Java Province, with an annual rice production of 787,000 tons. According to research by the Agricultural Research and Development Agency, this production generates approximately 725,000 tons of rice husk charcoal annually. Additionally, Grobogan produces 783,700 tons of corn annually, with approximately 35% (270,000 tons) of corn waste. Both rice husks and corncobs represent substantial opportunities for utilization as energy sources (Donald *et al.*, 2022). In Sugihmanik Village, Tanggungharjo, and Grobogan Regency, many SMEs have already used corn cobs and rice husks as fuel, but they do not process these materials into briquettes before use. Consequently, the production of charcoal from rice husks and corncobs poses adverse environmental consequences (Hartini *et al.*, 2023). When rice husks or corncobs are scarce, SMEs often resort to using firewood instead of processing biomass waste into briquettes, leading to deforestation. Conversely, the abundance of biomass waste during the harvest season leads to its frequent burning at the borders of agricultural fields. This scenario highlights the necessity of enhancing both the production and utilization of biomass briquettes, particularly in developing nations where there is an abundance of biomass waste (Obi *et al*., 2022).

Briquette quality test

Biomass and coal are solid fuels that have distinct chemical characteristics. Coal is known for its high carbon, calorific value, low ash, and volatile compound contents. In contrast, biomass has a high volatile material content but a lower carbon content. Variations in ash content within biomass are contingent upon the material type, and in general, the calorific value of biomass is inferior to that of coal. The elevated levels of volatile compounds present in biomass facilitate its ignition at reduced temperatures. However, the devolatilization process at low temperatures means that biomass is not easily ignited or burned. Combustion tends to be rapid and difficult to control (Yang *et al*. 2024). For briquettes to be considered of good quality, it is essential that they exhibit a smooth surface that does not leave any black stains on the hands. Additionally, as a fuel, briquettes must meet the following criteria: 1). Easy to ignite, 2). Smoke-free, 3). The combustion gases should be non-toxic, 4). Airtight and resistant to mold when stored for long periods, 5). exhibited a consistent combustion rate in terms of the time, burn rate, and temperature. Various processing variables, such as pressure, temperature, particle size, binding ratio, and moisture content, play a crucial role in determining the quality of the briquettes produced (Saeed *et al*., 2021). According to Lopez *et al*. (2020), both the raw materials and the final briquettes should have high energy and fixed carbon contents while maintaining low ash and volatile matter contents. Several tests need to be conducted to produce optimal briquette quality.

Calorific value

The calorific value is defined as the heat energy released during the combustion process of a material. An increased calorific value signifies an enhancement in the quality of the briquette (Ossei-Bremang *et al.*, 2024). According to Indonesian National Standard

(INS) No. 1/6325/2000, a briquette is considered to meet quality standards if it has a minimum calorific value of 5000 calories per gram (cal/g).

Moisture content

Moisture content was measured at each stage of the process because it is a key parameter for determining briquette quality. Several key factors are influenced by the moisture content, including the calorific value of combustion, the propensity for flammability, the efficiency of combustion, and the quantity of smoke emitted during the burning process. The presence of high moisture content in briquettes can adversely affect their combustion heat value, hinder the ease of ignition, and contribute to the generation of excessive smoke. According to the Indonesian National Standard No.1/6235/2000, the moisture content of briquettes should be less than 8%. Therefore, the lower the moisture content, the higher is the briquette quality.

Ash content

Ash is the residue of the unburned material after complete combustion, which is closely related to its inorganic materials. The presence of high ash content may diminish the calorific value; thus, as ash content increases, the calorific value tends to decrease (Sharma *et al.*, 2024). To adhere to quality standards, briquettes must be characterized by a low ash content, which is essential for reducing dust emissions and mitigating potential during combustion (Marreiro *et al.*, 2021). According to Indonesian national standard number 1/6235/2000, a good briquette has an ash content of less than 8%.

Fixed carbon (FC)

One of the key parameters for determining briquette quality is the fixed carbon content. Fixed carbon represents the percentage of carbon remaining after volatile compounds are released during combustion. It is important to distinguish between the total carbon content of the fuel, known as final carbon, and the considerable fraction that is emitted as hydrocarbons found in the volatile matter (Afra *et al.*, 2021). Fixed carbon refers to carbon in a free state, not combined with other compounds that remain after the volatile materials have been driven off during the analysis of solid waste samples. The quality of briquettes is significantly influenced by the fixed carbon content, with higher values of fixed carbon correlating with enhanced briquette quality (Afra *et al.*, 2021). According to Indonesian National Standard No. 1/6235/2000, a good briquette should have a fixed carbon content of more than 77%.

Research position

Numerous studies focused on briquettes produced from diverse biomass sources have indicated varying qualities. A comprehensive overview of these studies is provided in Table 1.

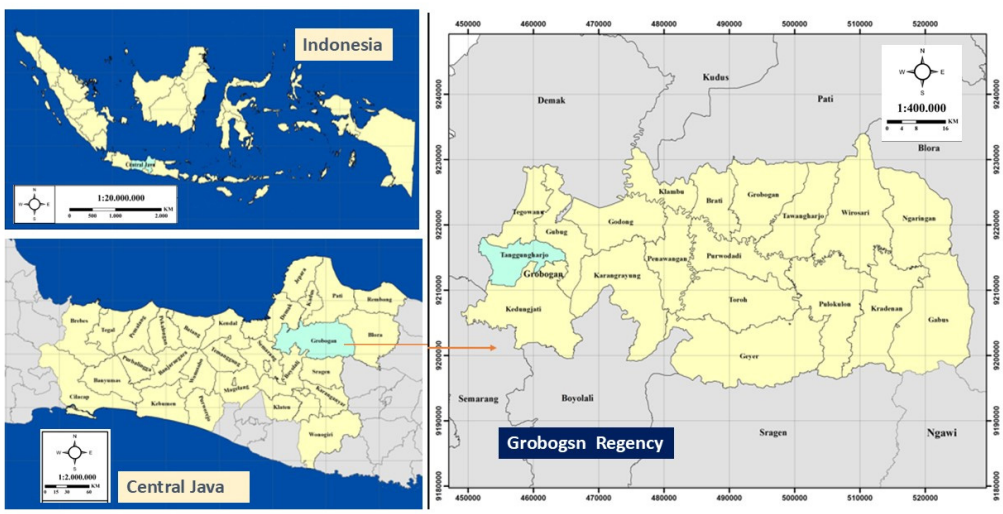

Fig. 1: Geographic location of the study area in Grobogan, Indonesia

Table 1: Results of biomass briquette tests from previous research and proposed position

Materials	Moisture Content (%)	Ash Content (%)	Fixed Carbon (%)	Calorific Value (%)	Sources
Corncob charcoal	3.62	4.84		5,653.99	Sukowati *et al.*, 2019
Corncob charcoal (0% Flour)	0.21	0.14		5,655,00	Wahyudi *et al.*, 2022
Corncob charcoal (3% Flour)	0.22	0.33		5,398,00	Wahyudi *et al.*, 2022
Tea leaf	5.39	3.14	25.86	7,222.95	Sukowati *et al.*, 2019
Charcoal coconut	3.71	3.38	93.14		Kurniati and Rezki, 2019
Shell cashew nut waste	5.30	4.96	72.62		Donald *et al.*, 2022
Banana peel, corn cob and coal mixture	5.14	6.06	62.62		Donald *et al.*, 2022
Bagasse and corn starch waste	6.86	8.59	42.92		Donald *et al.*, 2022
Banana leaf	7.17	10.70	14		Donald *et al.*, 2022
Banana tree waste	11.00	3.30			Donald *et al.*, 2022
Sugarcane pulp and coffee husks	4.40	12.00	64		Donald *et al.*, 2022
Sugarcane pulp	4.10	36.40	36.4		Donald *et al.*, 2022
Candlenut skin		7	21		Donald *et al.*, 2022
Durian skin	0.01	18.18	77.87	6,724.29	Donald *et al.*, 2022
Rice husk	48.51		20.93	3035	Osueke *et al.*, 2018
Corn cob	42.98		19.73	3850	Osueke *et al.*, 2018
Corncob without plastic	11.16	20.04	77.44	5,156.93	The current study
Corncob with 15% plastic	7.9	18.22	81.87	4,606.82	
Roasted corn cobs without plastic	1.59	39.42	59.93	5,442.08	
Roasted corn cobs with 15% plastic	1.23	22.76	77.24	5,296.09	
Rice husk without plastic	3.52	73.18	24.15	2,374.01	
Rice husk with 15% plastic	3.1	64.86	33.07	2,229.00	

Experimental design

An experimental framework was employed to investigate the essential parameters involved in the forming process and to establish their optimal values (Cai *et al.*, 2019). The experimental design method can be used to determine the most effective geometrical and operational parameters of the product forming process, as performed for soap-making products (Hartini *et al.*, 2021) and rubber pads (Kolahdooz *et. al.*, 2017). This experimental design was implemented to evaluate the best material combinations for achieving the production of high-quality briquettes. In this design, the combination of materials will be the independent variable, while the chemical characteristics will be the dependent variables. The dependent variables selected are informed by the parameters specified in the Indonesian National Standards, which include water content, calorific value, ash content, and fixed carbon. The combinations that have been developed are detailed in Table 2. Control variables are used to ensure consistency during product manufacturing. These factors consist of ensuring uniformity in the production stage, the quantity of water employed, and the timing and techniques applied during the drying process. By controlling for these factors, it is ensured that they remained consistent across all combinations.

Life cycle assessment

The environmental impact evaluation of biomass briquettes derived from olive pruning waste in Lebanon demonstrated that they yield more advantageous results in comparison to fossil fuels, with the exception of a few categories: “Non-carcinogenic”: 6.28E-04 kilogram vinyl chloride equivalent (kg C_2H_3Cl-eq), “Aquatic ecotoxicity”: 1.01E-02 kilogram tri-ethylene glycol (kg TEG water), “Terrestrial ecotoxicity” (5.04E-02 kg TEG soil), and “Land occupation” (9.37E-03 m² organic) (Saba *et al.*, 2020). In another study, the environmental LCA of briquettes made from 80% non-recyclable cardboard waste and 20% sawdust from a sawmill in Bolivia reported a global warming potential ranging from 23.9 to 26.7 grams of carbon dioxide equivalent per megajoule of energy (g CO_2-eq/MJ) (Ferronato *et al.*, 2022). The measured value was approximately 485% inferior to that of coal and 185% inferior to that of methane. These outcomes indicate that briquettes derived from cardboard waste and sawdust can

Table 2: Combination for experiment design

Combination	Composition per 1 kilogram (kg)	Amount of material
A_1B_1	Corncob + 0% PP	Corncob 1000 gram (g)
A_1B_2	Corncob + 15% PP	Corncob 850 g; PP 15%
A_2B_1	Roasted corn cobs + 0% PP	Roasted corncob 1000 g
A_2B_2	Roasted corn cobs + 15% PP	Roasted corncob 850 g; 15% PP
A_3B_1	Rice husk + 0% PP	Rice husk 1000 g
A_3B_1	Rice husk + 15% PP	Rice husk 850 g; 15 % PP

effectively reduce environmental repercussions and contribute to a lower. Silva *et al*. (2022) reviewed 150 articles on life cycle assessment of biomass briquettes and pellets in Latin America. Most studies were exploratory and focused on the thermomechanical properties of pellets and briquettes, comparing their environmental impacts. The global warming potential ranged from −68.7 g CO_2-eq (Chilean pellets) to 103 g CO_2-eq (Brazilian charcoal briquettes) per functional unit. The most favorable scenario was observed for briquette production in Brazil. Several studies on LCA of biomass briquettes have been conducted in Indonesia. The research conducted by Agustiar *et al*. (2023) indicates that converting palm oil waste into briquettes to replace coal can significantly diminish solid waste output in palm oil mills in the Barsela area of Aceh Province by 800 tons each year, while also contributing to a reduction in global warming potential (GWP). The use of sorghum biomass in Flores Indonesia, as much as 48 tons/ha/y to 4.8 million tons of pellets, can produce 8,300 GWh of electricity. By adopting this strategy, it is possible to lessen the influence of global warming by 7.9 million tons of CO2-equivalent, which corresponds to an 85% decrease in GHG emissions (Wiloso *et al*., 2020). LCA involves several stages: defining the goals and scope of the assessment, conducting a life cycle inventory, performing a life cycle impact analysis (LCIA), and interpreting results (Hartini *et al*., 2023). Within the LCIA phase, there are several key stages: characterization, normalization, weighting, and the calculation of a single score (Sari *et al*., 2023). The LCA framework has been used for life cycle assessment of the recycling process of used cooking oil into soap (Hartini *et al.,* 2021), tofu waste into the other product (Hartini *et al*., 2024), and furniture waste into toothbrushes (Hartini *et al*., 2022). According to ISO 14044, LCA studies can have various scopes, each with specific limitations: 1) Cradle-to-Grave: This scope assesses the entire process from raw material extraction, through production, energy production, and transportation, to the end of the product's life cycle; 2) Cradle-to-Gate: This scope assesses the entire process from the extraction of raw materials to the conclusion of the production phase, excluding considerations of transportation and usage; 3) Gate to Grave: This scope assesses the product from the end of the production stage through its use and final disposal, excluding the initial stages of raw material extraction and production; 4) The Gate-to-Gate framework involves the examination of specialized unit processes, covering the entire spectrum from the intake of raw materials to the conclusion of the production cycle.

Research framework

This study aimed to identify the optimal combination of briquettes made from biomass waste, specifically corn cobs, burnt corn cobs, burnt rice husks, and polypropylene waste, by evaluating their chemical characteristics and environmental impacts. The study began with an experimental design involving six different briquette combinations. The investigation initiated with an experimental setup featuring six varied briquette combinations. These combinations were subsequently assessed for their environmental implications utilizing a LCA approach. Finally, an analysis is conducted to determine the best combination, followed by recommendations based on the findings. The briquettes were tested in the laboratory according to the parameters of the Indonesian National Standard. In addition to quality testing, the study conducted an environmental impact analysis of every 1 kg of briquette with a life cycle assessment. The study framework is illustrated in Fig. 2.

The focus of this study is gate-to-gate, specifically evaluating the environmental effects associated with the production of 1 kg of briquettes. The life cycle inventory calculates the material and energy needed

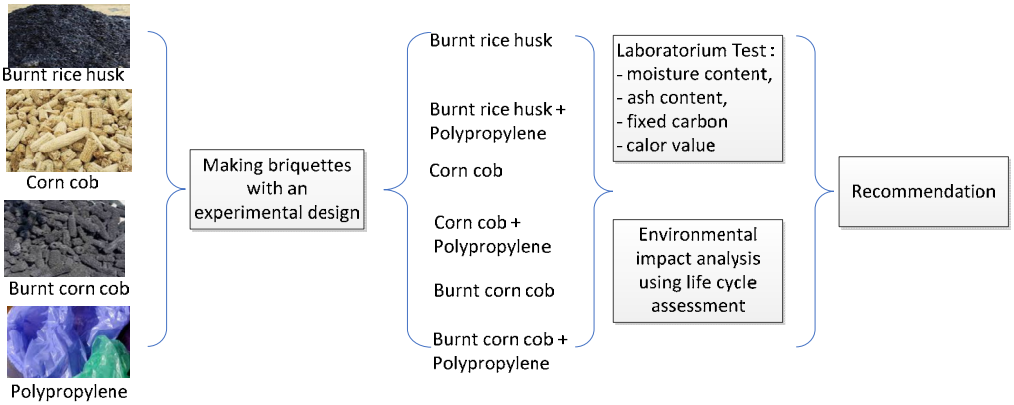

Fig. 2: The study framework

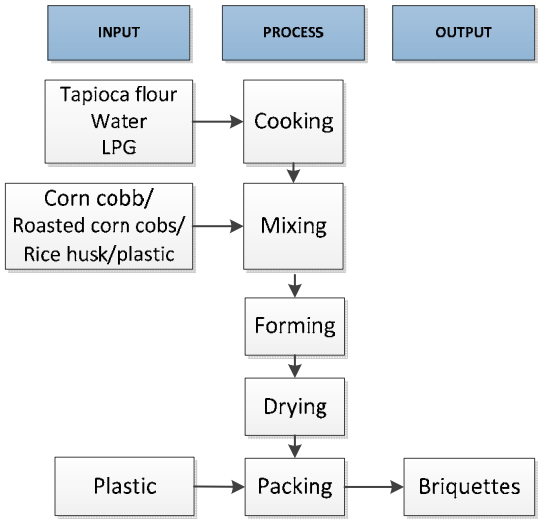

Fig. 3: Stages of making briquettes

to make 1 kg of briquettes based on a combination of experimental designs. The sequence of the manual briquette making process is shown in Fig. 3. Life cycle Impact analysis was carried out using Simapro V 9.5.0.2 with eco-cost 2024 versi 1.0. The focus of this study is gate-to-gate, emphasizing the analysis of biomass waste that has been processed and is ready for transformation into briquettes suitable for use.

RESULTS AND DISCUSSION

The research was conducted at a tofu SME in Sugihmanik Village, Grobogan, which uses corncobs and rice husks as energy sources for boiling tofu porridge and frying tofu. Its production capacity is approximately 4,000 kg of soybeans per day, generating approximately 1,000 kg of combustion waste daily, which is currently discarded and not utilized. This study aims to explore the potential of using burnt corncobs and burnt rice husks as briquette materials when mixed with plastic waste. The study also compared these combinations with briquettes made from raw corncobs.

The result of chemical characteristics test

Table 3 provides a summary of the experimental outcomes for the formulated combination. As indicated in Table 3, the moisture levels of the briquettes largely conformed to Indonesian standards, with the notable exception of those derived from raw corn cobs. Briquettes produced from burnt corncobs

Table 3: The experimental result

Combination	Chemical characteristic tests			
	Moisture content (%)	Ash content (%)	Fixed carbon (%)	Calorific value (Cal/gr)
A_1B_1	11.16	20.04	77.44	5,156.93
A_1B_2	7.9	18.22	81.87	4,606.82
A_2B_1	1.59	39.42	59.93	5,442.08
A_2B_2	1.23	22.76	77.24	5,296.09
A_3B_1	3.52	73.18	24.15	2,374.01
A_3B_1	3.1	64.86	33.07	2,229.00
INS standard	Max 8	Max 8	Min 77	Min 5,000

and burnt husks complied with the INS standard, as their moisture content was below 8%. In contrast, briquettes made from raw corncobs exceeded this threshold. This implies that achieving an acceptable moisture level in raw corn cobs requires either a prolonged drying process or an increase in drying temperature.

Additionally, the inclusion of plastic waste as a mixed material positively affected the moisture content. The findings indicate that formulations containing plastic demonstrate reduced moisture levels, as plastic is not capable of water absorption. The ash content test for all combinations ranged from 24.15% to 73.18%, which significantly exceeded the Indonesian Standard, which stipulates that ash content should be below 8%. These results indicated that none of the briquette combinations met the INS standard. he significant ash content results from the utilization of burnt rice husk and corn cob, both of which are combustion by-products generated by SMEs. However, the inclusion of plastic waste appears to reduce the ash content of briquettesOf all the combinations evaluated, the most favorable result was produced by the blend of corncob charcoal and plastic, which led to an ash content of 22.76%. Testing the fixed carbon parameter across all combinations yielded values ranging from 24.15% to 81.87%. Briquettes made from corncobs have a high fixed carbon content and meet the Indonesian Standard of more than 77%. Conversely, briquettes derived from rice husks demonstrated a diminished fixed carbon content, which did not satisfy the standard, as their measurements were under 77%. These results indicate that briquettes made from corncobs are superior to those made from rice husks in terms of the fixed carbon content. Additionally, experiments revealed that the inclusion of plastic waste can increase the fixed carbon content. Testing the calorific value parameter across all combinations resulted in values between 2,229.00 and 5,442.08. According to the Indonesian Standard, briquettes must have a calorific value of more than 5,000. Table 3 indicates that briquettes drived from corncobs typically satisfy the established standard, while those derived from burnt rice husks do not, exhibiting a calorific value that is less than 5,000. This study concludes that briquettes made from corncobs have a better calorific value than burnt rice husk briquettes. This result is in line with Osueke *et al*. (2018), who stated that corncobs have a higher calorific value than rice husks, which means that corncobs are more flammable than rice husks and are a viable substitute for fossil fuels. The calorific value of corncob-based briquettes is greater than 5000 according to Sukowati *et al*., (2019) research, which mixed corn cob briquettes with teak leaves. In the evaluation of briquettes, the calorific value and fixed carbon are usually regarded as the most important factors influencing their quality and efficiency. However, moisture content is also essential, as high humidity can significantly reduce the combustion efficiency (Saeed *et al*., 2021). Monitoring ash content is significant because it can influence both the quality of combustion and various environmental factors (Sharma *et al*., 2024). Therefore, a comprehensive assessment of these parameters is necessary to ensure the quality of briquettes.

The result of life cycle assessment

Chemical characteristic tests on all combinations found that the mixed plastic corncobs met the Indonesian Standard, except for the Ash Content parameter. In terms of quality, the corncobs were found to be of a higher standard than the scorched husks produced during the combustion of tofu SMEs. Furthermore, all designed combinations underwent

environmental impact analysis with an LCA. The LCA results of the corncobs are presented in Tables 4 and 5.

The results of a single score for all the combinations are shown in Fig. 4.

The single-score results for all these combinations are listed in Table 6.

From Table 4, it can be seen that the largest impact occurs in the ecotoxicity category which is accounted to 48.4 CTUe or if converted into the single score, it is aaccounted as much as USD 0.162. The impact of biomass waste conversion into briquettes on ecotoxicity is determined by multiple elements, including the characteristics of the raw materials, the methods employed during production, and the ways in which the briquettes are utilized. This is related to the following reasons: 1) Biomass waste can contain hazardous chemicals, including toxic organic compounds such as polyaromatic hydrocarbons and heavy metals such as cadmium, arsenic, and lead. When biomass is used to produce briquettes, the combustion process releases harmful substances into the environment. These substances have the potential to be released into the air or found in ash, which could contribute to the pollution of water, air, and soil (Yang *et al.*, 2016); 2) Biomass combustion generates ash that can be rich in heavy metals and other toxic compounds in substantial amounts. These contaminants have the potential to cause pollution in soil and water, thereby harming microorganisms and vegetation (Wyszkowska *et al.*, 2024); 3) The combustion of biomass for briquette production can generate pollutants including particulate matter (PM), nitrogen oxides (NOx), sulfur dioxide (SO_2), and volatile organic compounds (VOCs). The release of these emissions poses a significant threat to both air quality and the overall health of ecosystems. The accumulation of fine particulate matter and hazardous gases in the environment can lead to detrimental effects on soil, water, and air (Zhang

Table 4: Characteristic results of corn cob briquettes without plastic

Impact category	Unit	Total	Cooking	Mixing	Forming	Drying
Carbon footprint	kg CO_2 eq	0.482	0.0672	0.138	0.138	0.138
Acidification	Mol H^+ eq	0.00175	0.000173	0.000524	0.000524	0.000524
Eutrophication	kg PO_4 eq	0.012	0.00273	0.00309	0.00309	0.00309
Photochemical ozone form	kg NOx eq	0.00117	0.000238	0.000312	0.000312	0.000312
Particulate matter	kg $PM_{2.5}$	6.57 E-5	1.4 E-5	1.72 E-5	1.72 E-5	1.72 E-5
Human toxicity, cancer	Comparative toxicity unit for humans (CTUh)	2.36E-10	3.86E-11	6.58E - 11	6.58E - 11	6.58E - 11
Human toxicity, non-cancer	CTUh	1.23E-8	2.31E-9	3.34E-9	3.34E-9	3.34E-9
Ecotoxicity, freshwater	Comparative toxic unit for freshwater ecosystem	48.4	1.4	15.7	15.7	15.7
Metals scarcity	Inited States dollar (USD)	0.002811	0.000703	0.000703	0.000703	0.000703
Use fossil based plastics	kg oil equivalent	x	x	x	x	x
Use uranium	USD	0.00087	0.000137	0.000244	0.000244	0.000244
Land use	biofactor	0.00129	0.000323	0.000324	0.000324	0.000324
Baseline water stress	m^3 equipment	0.0235	0.00588	0.00588	0.00588	0.00588
Landfill	USD	x	x	x	x	X

Table 5: Single score results of corn cob briquettes fwithout plastic

Impact category	Unit	Total	Cooking	Mixing	Forming	Drying
Carbon footprint	USD	0.0744	0.0104	0.0214	0.0214	0.0214
Acidification	USD	0.0155	0.00153	0.00465	0.00465	0.00465
Eutrophications	USD	0.0749	0.017	0.0193	0.0193	0.0193
Photochemical ozone form	USD	0.00833	0.00169	0.00221	0.00221	0.00221
Particulate matter	USD	0.00306	0.00065	0.000802	0.000802	0.000802
Human toxicity, cancer	USD	0.000252	4.12E-5	7.03E-5	7.03E-5	7.03E-5
Human toxicity, non-cancer	USD	0.00309	0.000579	0.000837	0.000837	0.000837
Ecotoxicity, freshwater	USD	0.162	0.00471	0.0525	0.0525	0.0525
Metals scarcity	USD	0.00291	0.000728	0.000728	0.000728	0.000728
Use fossil based plastics	USD	X	X	X	X	X
Use uranium	USD	0.000902	0.000142	0.000253	0.000253	0.000253
Land use	USD	0.0103	0.00258	0.00258	0.00258	0.00258
Baseline water stress	USD	0.0312	0.00781	0.00781	0.00781	0.00781
Landfill	USD	x	X	x	x	x
Total		0.387	0.0479	0.113	0.113	0.113

et al., 2023). 4) Collecting biomass for briquette production can lead to habitat destruction and land degradation. Excessive use of biomass waste can disrupt the ecosystem balance, resulting in the loss of biodiversity and further degradation of land (Zhang *et al.,* 2023). The environmental consequences associated with the utilization of biomass waste for briquette manufacturing predominantly stem from the existence of toxic substances within the waste, the combustion process itself, the application of combustion residues, and the risks of habitat destruction and land degradation. Using plastics in briquettes can exacerbate environmental impacts, particularly in the climate change category. Polypropylene plastic, in particular, contributes to increased climate change effects due to various factors associated with its entire life cycle, from production through to disposal (Geyer *et al*., 2017): 1) Derived from petroleum or natural gas, polypropylene plastic undergoes a production process that demands substantial energy. This energy is largely sourced from fossil fuel combustion, contributing to greenhouse gas emissions, including CO_2; 2) polypropylene plastic takes hundreds of years to decompose. Over the course of this extended degradation phase, there is a possibility that microplastics will be released into the environment, leading to their accumulation in ecosystems and their eventual entry food chains; 3) Burning plastic releases greenhouse gases and other pollutants, such as dioxins, which not only contribute to climate change but also pose risks to human health; 4) burning plastic using fossil fuels contributes to greenhouse gas emissions; 5) An escalation in plastic usage correlates with an increase in fossil fuel extraction, which has detrimental effects on the environment, including a rise in CO2 emissions, the loss of habitats, and a decline in biodiversity as a consequence of resource exploitation.

Implication and recommendation

(i) Theoretical Implications

This study identified the chemical properties and environmental impacts of combining corncobs and burnt rice husks. The outcomes of the experimental design, which consists of fabricating briquettes from a blend of corncobs, burnt rice husks, and polypropylene, play a crucial role in furthering the research on renewable energy sourced from waste products. The results of the recapitulation of chemical characteristics and environmental impacts show that briquettes from corncobs have better results than burnt rice husks. The briquettes that have minimal environmental impact are corncobs without plastic. The recapitulation results are shown in Table 7. Based

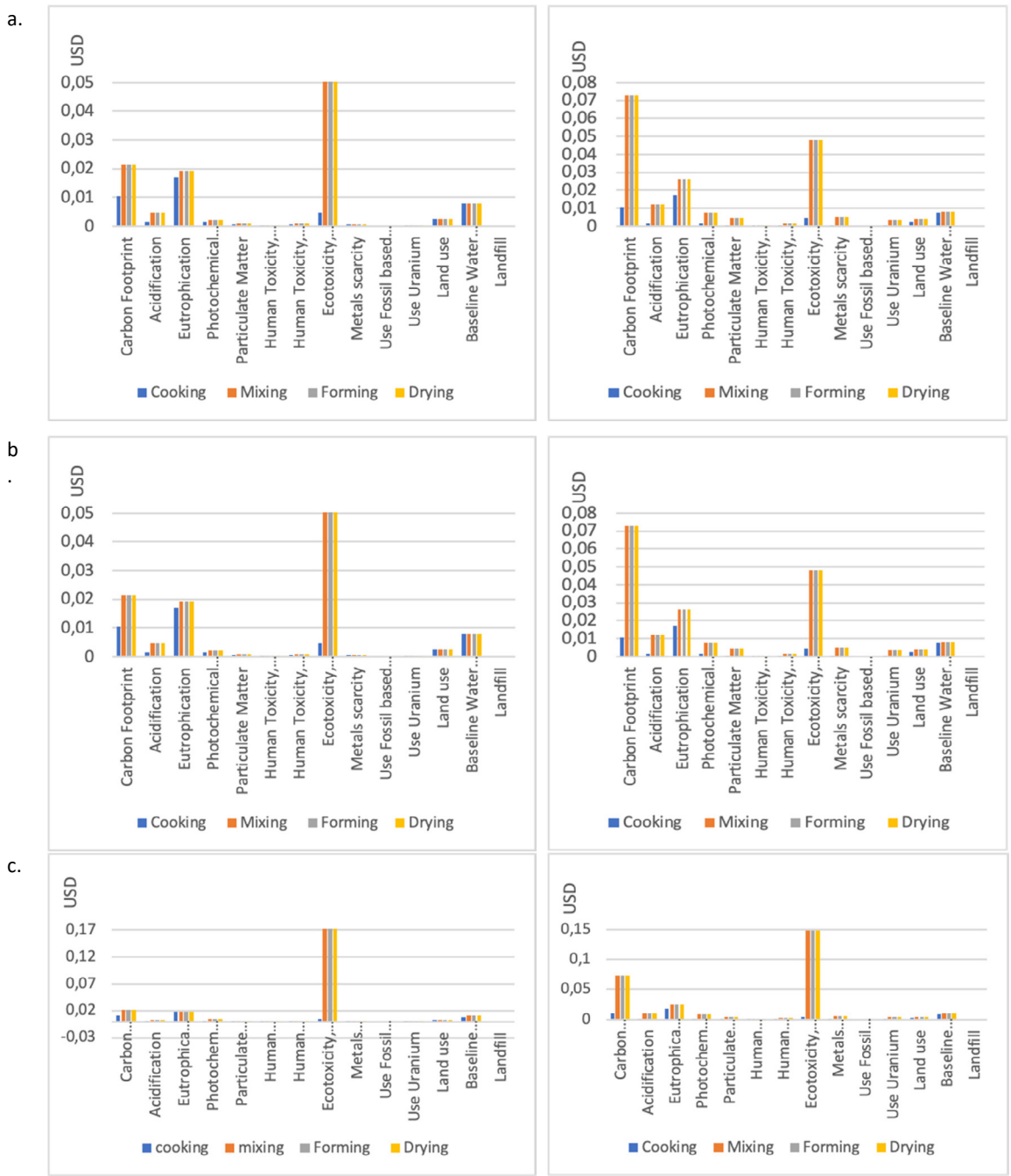

Fig. 4: The results of the single score of (a). corn cob 0% PP and corn cob 15% PP, (b). burnt corn cob 0% PP and burnt corn cob 15% PP (c). burnt rice husk 0% PP and burnt rice husk 15% PP

on the findings, plastic-free corn cob briquettes can be recommended as alternative energy sources. However, it is essential to conduct a thorough analysis of the combustion process to ensure that the resulting water and ash contents align with the national standards set by Indonesia.

Table 6: The single score results of all these combinations

Damage category	Roasted corn cobb		Corn cobb		Rice husk	
	0P 5T	15P 5T	0P 5T	15P 5T	0P 5T	15P 5T
Carbon footprint	0.0744	0.229	0.0744	0.229	0.0735	0.228
Acidification	0.0155	0.0384	0.0155	0.0384	0.00757	0.0317
Eutrophication	0.0749	0.0952	0.0749	0.0952	0.0714	0.0922
Photochemical ozone form	0.00833	0.0238	0.00833	0.0238	0.0126	0.0274
Particulate matter	0.00306	0.0135	0.00306	0.0135	0.00355	0.0139
Human toxicity, cancer	0.000252	0.00048	0.000252	0.00048	0.000253	0.000481
Human toxicity, non-cancer	0.00309	0.00455	0.00309	0.00455	0.00541	0.0065
Ecotoxicity, freshwater	0.162	0.149	0.162	0.149	0.517	0.448
Metals scarcity	0.00291	0.0158	0.00291	0.0158	0.00339	0.0162
Use fossil based plastics	X	X	X	X	X	X
Use uranium	0.000902	0.0109	0.000902	0.0109	0.000772	0.0108
Land use	0.0103	0.0151	0.0103	0.0151	0.0106	0.0154
Baseline water Stress	0.0312	0.0319	0.0312	0.0319	0.0387	0.0381
Landfill	x	X	x	X	x	X
Total (USD)	0.387	0,627	0.387	0,627	0,745	0.928

Table 7: Recapitulation of chemical characteristics and environmental impacts

Code	Combination of experiment design	Chemical characteristic tests				Life cycle impact assessment (USD)
		Moisture content	Ash content	Fixed carbon	Calorific Value	
A_1B_1	Corncob + 0% P P	11.16	20.04	77.44	5,156.93	0.387
A_1B_2	Corncob + 15% PP	7.90	18.22	81.87	4,606,82	0.627
A_2B_1	Roasted corn cobs + 0% PP	1.59	39.42	59.93	5,442.08	0.387
A_2B_2	Roasted corn cobs + 0% PP	1.23	22.76	77.24	5,296.09	0.627
A_3B_1	Rice husk + 0% PP	3.52	73.18	24.15	2,374.01	0.745
A_3B_1	Rice husk + 15% PP	3.1	64.86	33.07	2,229.00	0.928
Standard		Max 8	Max 8	Min 77	Min 5,000	-

(ii) Managerial implications

According to the Central Statistics Agency Census, Grobogan Regency's agricultural production in 2021 reached 850 thousand tons of rice and 830 thousand tons of corn. Given that corncobs and husks constitute approximately 30% of the total corn production, approximately 255 thousand tons of husks and 250 thousand tons of cobs are produced each year as biomass waste. This extensive availability of biomass offers significant prospects for its development as a renewable energy source, particularly in conjunction with fossil fuels through co-firing practices. In the Grobogan Regency, a cement factory launched a program to co-fire coal with biomass waste. The factory's daily requirement for this fuel is approximately 100 tons, or 300 thousand tons per year. The market for biomass briquettes in the Grobogan Regency indicates a noteworthy potential, representing 50% of the total biomass waste capacity, which is estimated to be about 500 thousand tons annually. This research will assist local governments in guiding the production of biomass briquettes that meet consumer quality standards while minimizing environmental impacts. Moreover, it is essential to empower communities to actively participate in the collection of agricultural waste. The behavior exhibited by these communities plays a pivotal role in determining the success of waste collection initiatives (Hartini *et al.*, 2019).

(iii) Recommendation

The requirements for passing the briquette test for coal co-firing, as set by the cement factory in Grobogan, include three key parameters: a minimum calorific value of 4000 kilocalories per kilogram (kcal/kg), maximum ash content of 10%, and maximum moisture content of 25%. According to the results displayed in Table 6 regarding the chemical characteristics, every combination achieved the necessary moisture content levels; however, none complied with the required ash content standards. Regarding calorific value, only briquettes made from corncobs have calorific values greater than 4000 kcal/kg. The findings of this study indicate the necessity for further exploration of biomass briquettes produced from corncobs, with a focus on their viability as a renewable energy alternative or for use in cofiring alongside fossil energy sources. Corn cobs meet the requirements for moisture content and calorific value, but not for ash content. The combination of corncobs without a plastic mixture is recommended because it not only meets the chemical characteristics but also has a smaller environmental impact. This recommendation can act as a framework for local administrations to create briquettes from corn cobs, which would help decrease agricultural waste and alleviate the environmental consequences in Grobogan Regency. Wiloso *et al*. (2020) conducted modeling to determine whether implementing 5% co-firing in all coal-fired power plants in Indonesia would require 3.05 million tons of pellets. This effort will reduce the impact of global warming by 5.28 million tons of CO_2-eq from 118 million tons of CO_2-eq per year (GHG savings of 4%).

CONCLUSION

Grobogan Regency, the largest producer of rice and corn in Central Java, Indonesia, has significant potential to produce large amounts of biomass waste that have not yet been utilized optimally. The utilization of biomass waste as a primary material for briquette manufacturing presents an opportunity for alternative energy generation. The study employed an experimental design featuring six variations of briquettes created from a mixture of husks, corncobs, and plastic waste. The chemical characteristics were tested based on parameters such as the heat, fixed carbon, ash content, and moisture content. In addition, the ecological effects of each combination were determined using life cycle assessment methodologies. The study examined six distinct combinations of briquettes derived from burnt rice husks, corncobs, and polypropylene plastic. The combination includes corncobs without polypropylene, corncobs with 15% polypropylene, roasted corncobs without polypropylene, roasted corncobs with 15% polypropylene, rice husk without polypropylene, and rice husk with 15% polypropylene. Among the six combinations, moisture content, ash content, fixed carbon content, and calorific value were examined as independent variables. The next stage analyzed the environmental impact of the six combinations using life cycle assessment with the help of SimaPro software. The study indicated that corn cob briquettes, when produced without the inclusion of plastic, exhibited superior chemical properties and more favorable environmental effects. Corncobs without polypropylene had a moisture content of 11.16%, an ash content of 20.04%, a fixed carbon content of 77.44%, and a calorific value of 5,156.93 cal/g. The environmental impact was equivalent to an eco-cost of USD 0.387. The environmental impact value based on 14 impact categories after the normalization stage is as follows: carbon footprint USD 0.0744, acidification USD 0.0155, eutrophication USD 0.0749, photochemical ozone from USD 0.00833, particulate matter USD 0.00306, human toxicity, cancer USD 0.000252, human toxicity, non-cancer USD 0.00309, ecotoxicity, freshwater USD 0.162, metal scarcity USD 0.00291, use fossil-based plastics USD X (none), use uranium USD 0.000902, land use USD 0.0103, baseline water stress USD 0.0312, and landfill USD X (none). The greatest impact occurred in the ecotoxicity category. The production of briquettes from biomass waste affects ecotoxicity, which can be attributed to multiple factors concerning the raw materials utilized, the processes involved in their production, and the manner in which the briquettes are employed. This can be attributed to the following reasons: 1). Biomass wastes can contain hazardous chemicals, 2). The residue resulting from the burning of biomass can include significant amounts of heavy metals and other harmful chemical constituents, 3). The combustion of biomass for briquette production can generate pollutants; 4). Collecting biomass for briquette production can lead to habitat destruction and land degradation. The limitations of this study are primarily attributed to the restricted availability of material sources, particularly the waste generated from

the combustion of (SMEs involved in tofu production. Temperature settings during burning and the potential mixing of corn cob skin with a high mineral content tend to leave more ash residue. Conducting further studies on biomass waste originating from agricultural products that receive specific treatments for briquette production could prove beneficial in elevating the quality of briquettes, particularly by decreasing the ash content. The ash content of sawdust briquettes was the lowest at 0.4%. Future studies might examine the potential of using sawdust as an additive in briquette materials to lower the ash content. The current study could provide valuable insights for the community, encouraging the use of corn cob waste in briquette manufacturing rather than its disposal as biomass waste. These briquettes can be used to co-fire coal in a cement factory in Grobogan. Additionally, a study of circular economy-based business planning is crucial before launching a corn-cob briquette venture. Findings from this study suggest that the blending of plastics during the fabrication of biomass briquettes is associated with a reduction in calorific value, as well as lower water and ash content. Therefore, plastic waste is better processed into refuse-derived fuel (RDF) than used as a mixture of biomass briquettes. Investigating the recycling of plastic waste into RDF for co-firing in cement factories is a promising area for future research. Once the most effective combination has been determined, it is essential to conduct further research to analyze the challenges and obstacles that may arise in the implementation of briquettes as a replacement for fossil energy or in conjunction with fossil fuels in industrial settings. Furthermore, the circular economy-based business model (CEBM) for biomass briquettes in Grobogan is interesting for future research. In the context of sustainable development, it is important to consider resource efficiency and reuse and recycling of waste as significant environmental measures. CEBM aims to reduce the amount of waste that ends up in landfills, reduce harmful emissions, and maintain sustainability of the raw materials used. Within the framework of a sustainable economy, the management of waste is pivotal in ensuring the retention of valuable materials throughout their life cycle, facilitated by recycling and waste recovery initiatives.

AUTHOR CONTRIBUTIONS

M.N. Rashif conducted a literature review, data collection, and processing of experimental and life cycle assessment data and prepared the text. S. Hartini conducted experimental design, analyzed and interpreted the results of the life cycle assessment. D.P. Sari conducted an analysis of experimental results and recommendations. B.S. Ramadan analyzed the results of the life cycle assessment. T. Matsumoto reviewed and approved the final version of the manuscript. A.T. Balasbaneh reviewed and approved the final version of the manuscript.

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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

%	Percent
°C	Degree of Celsius
cal/g	Calor per gram
CEBM	Circular economy-based business model
CO_2	Carbon dioxide
CTUe	Comparative toxic unit for freshwater ecosystem
CTUh	Comparative toxicity unit for humans
EU	European Union
Fig.	Figure
g	Gram
g CO_2-eq .MJ	Grams of carbon dioxide equivalent per megajoule of energy
GHG	Greenhouse gas
GWP	Global warming potential
ha	Hectare
HDPE	High-density polyethylene
INS	Indonesian National Standard
kg	Kilogram
kcal/kg	kilocalories per kilogram
kg C_2H_3Cl_eq	Kilogram vinyl chloride equivalent
kg CO_2	Gram carbon dioxide equivalent
kg TEG	Kilogram tri-ethylene glycol
kWh	KiloWatt hours
LCA	Life cycle assessment
LCI	Life cycle inventories
LCIA	Life cycle impact assessment
LDPE	Low-density polyethylene
m^2	Square meter
m^3	Meter cubic
mg/L	Miligram per liter
MJ/kg	Mega Joule per kilogram
mm	Milimeter
mol H+ eq	Mol of the hydrogen ion concentration (H+)
Mol H+eq	Moles hydrogen ion equivalent
NMVOC-eq	Non-methane volatile organic compound equivalents
NOx	Nitrogen oxide
(NOx)eq	Nitrogen oxide equivalent
PET	Polyethylene Terephthalate
PM	Particulate matter
PO4eq	Phospate equivalent
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
RDF	refuse derived fuel
SMEs	Small- and medium-sized enterprises
Tons/ha/y	Tons per hectare year
USD	United States Dollar

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AUTHOR (S) BIOSKETCHES

Rashif, M.N., M.Sc. Student, Department of Industrial Engineering,
Faculty of Engineering, Universitas Diponegoro, Prof. Sudarto S.H., Tembalang, Semarang, Indonesia.
- Email: *nashirrashif@students.undip.ac.id*
- ORCID: 0009-0004-2830-4644
- Web of Science ResearcherID: -
- Scopus Author ID: 58788563000
- Homepage: https://sites.google.com/view/nashirrashif/home

Hartini, S., Dr., Professor, Lean and Sustainable Supply Chain Laboratory, Department of Industrial Engineering, Faculty of Engineering, Universitas Diponegoro, Indonesia
- Email: *srihartini@lecturer.undip.ac.id*
- ORCID: http://orcid.org/0000-0001-5659-6083
- Web of Science ResearcherID: AAR-8230-2021
- Scopus Author ID: 57216575988
- Homepage: https://industri.ft.undip.ac.id/en/sri-hartini-3/

Sari, D.P., Dr., Assosiate Professor, Lean and Sustainable Supply Chain Laboratory, Department of Industrial Engineering, Faculty of Engineering, Universitas Diponegoro, Indonesia.
- Email: *dianapuspitasari@lecturer.undip.ac.id*
- ORCID: http://orcid.org/0000-0003-1989-8925
- Web of Science ResearcherID: AAD-4408-2022
- Scopus Author ID: 57205627395
- Homepage: https://industri.ft.undip.ac.id/diana-puspita-sari/

Ramadan, B.S., Ph.D., Assistant Professor, Environmental Sustainability Research Group, Department of Environmental Engineering, Faculty of Engineering, Universitas Diponegoro, Jl. Prof. Sudarto S.H., Tembalang, Semarang City, Central Java 50275, Indonesia.
- Email: *bimastyaji@live.undip.ac.id*
- ORCID: 0000-0002-5194-0743
- Web of Science ResearcherID: AEK-7799-2022
- Scopus Author ID: 57216575988
- Homepage: https://lingkungan.ft.undip.ac.id/bsr-2/

Matsumoto, T., Ph.D., Professor, Institute of Environmental Science and Technology, The University of Kitakyushu, 1-1, Hibikino, Wakamatsu-ku, Kitakyushu, Fukuoka, 808-0135, Japan.
- Email: *matsumoto-t@kitakyu-u.ac.jp*
- ORCID: 0000-0002-3191-2681
- Web of Science ResearcherID: NA
- Scopus Author ID: 55694808300
- Homepage: https://www.kitakyu-u.ac.jp/env/lang-en/faculty/life/toru-matsumoto.html

Balasbaneh, A.T., Dr., 5LSBU Business School, London South Bank University, 103 Borough Road,
London SE1 0AA, United Kingdom.
- Email: *ali.tighnavard-balasbaneh@lsbu.ac.uk*
- ORCID: 0000-0002-7823-0477
- Web of Science ResearcherID: NA
- Scopus Author ID: 59203454600
- Homepage: https://www.lsbu.ac.uk/research/centres-groups/energy,-materials-and-environment-research-centre#content2-406901

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