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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.

NUMBER OF REFERENCES
55

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7

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3

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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

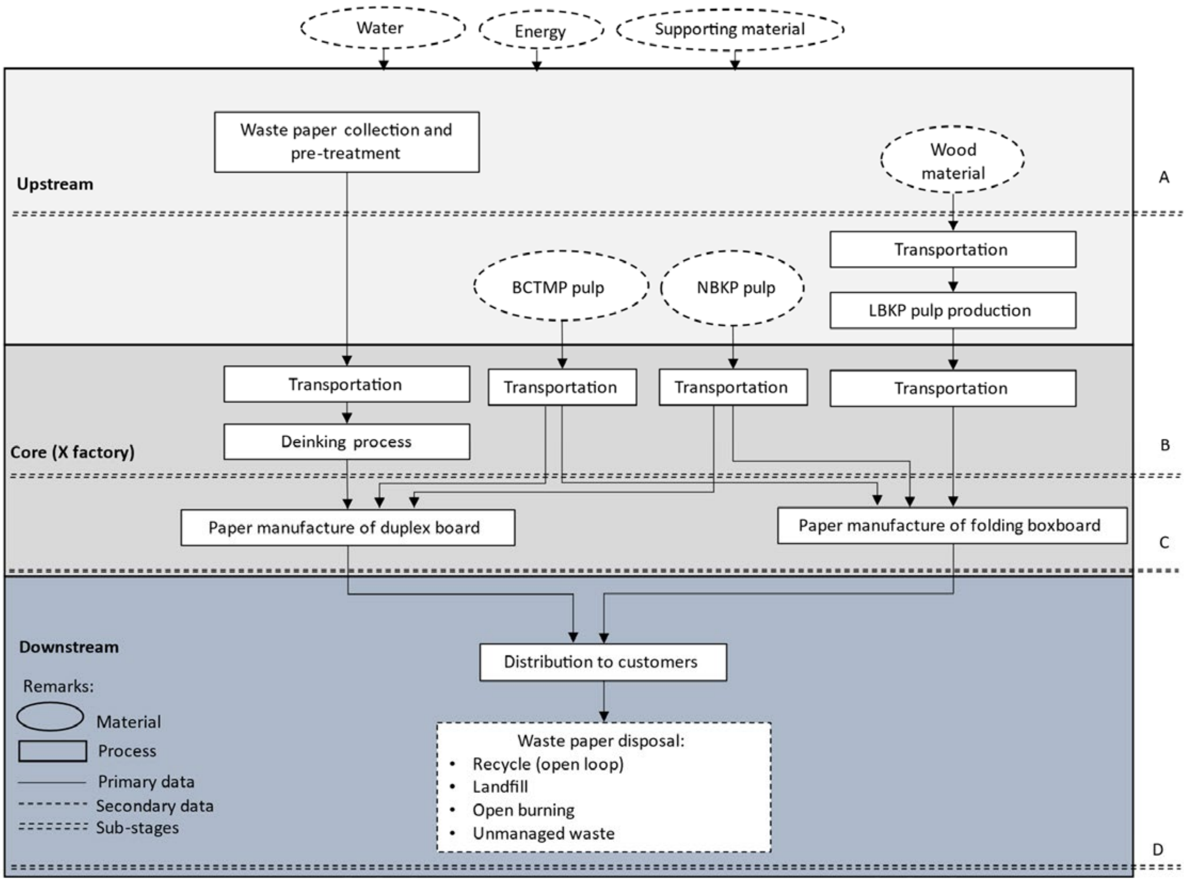

Fig. 1: Scope of life cycle stages of the study from cradle to grave

(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

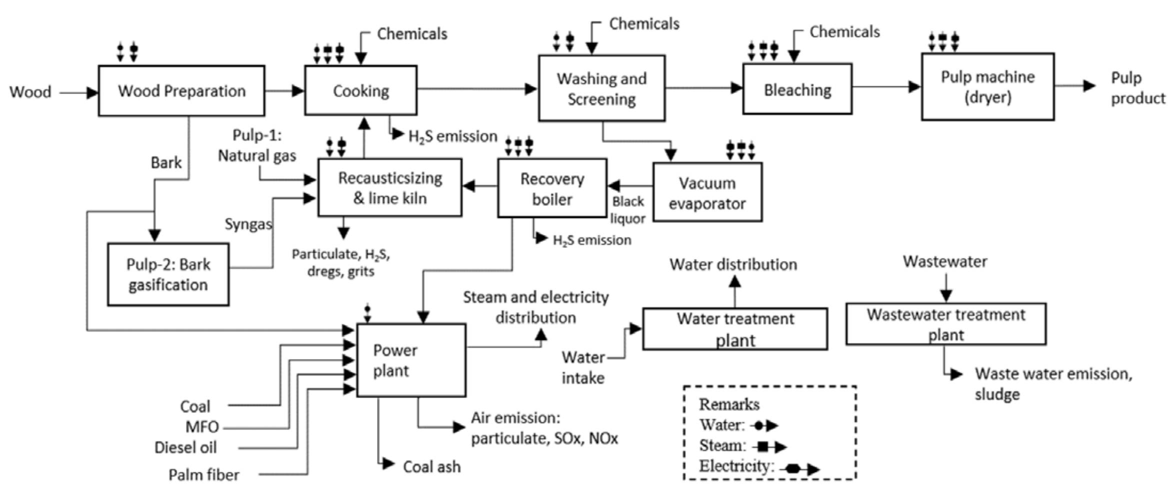

Fig. 2: Flow diagram of production process of pulp production in pulp-1 and pulp-2 factory

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

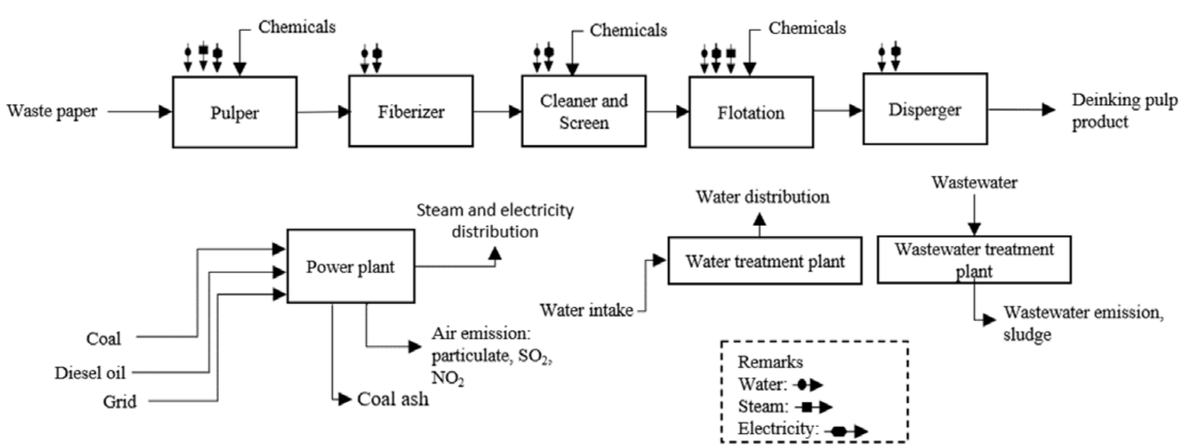

Fig. 3: Flow diagram of deinking pulp production in X factory

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 $PM_{2.5}$

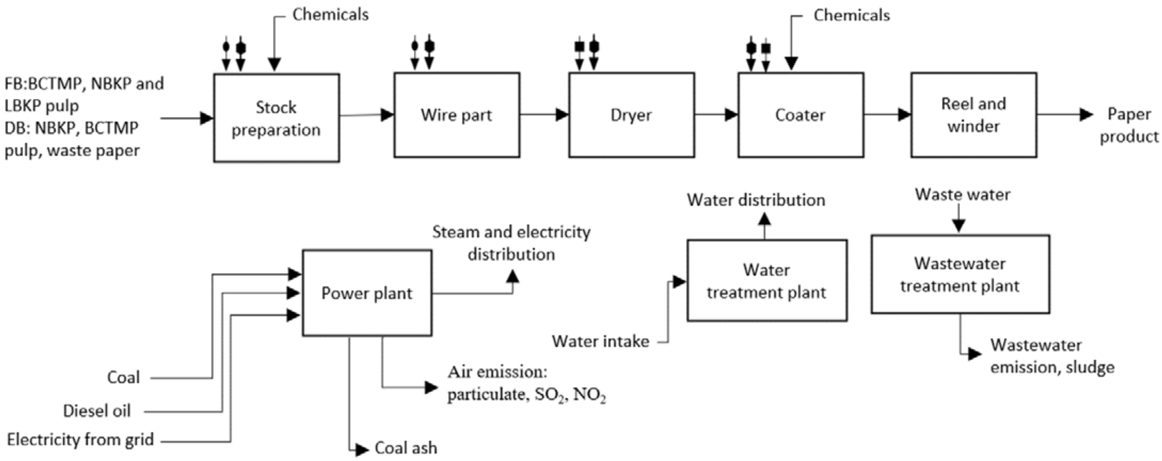

Fig. 4: Flow diagram of FB and DB paper production in X Factory

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

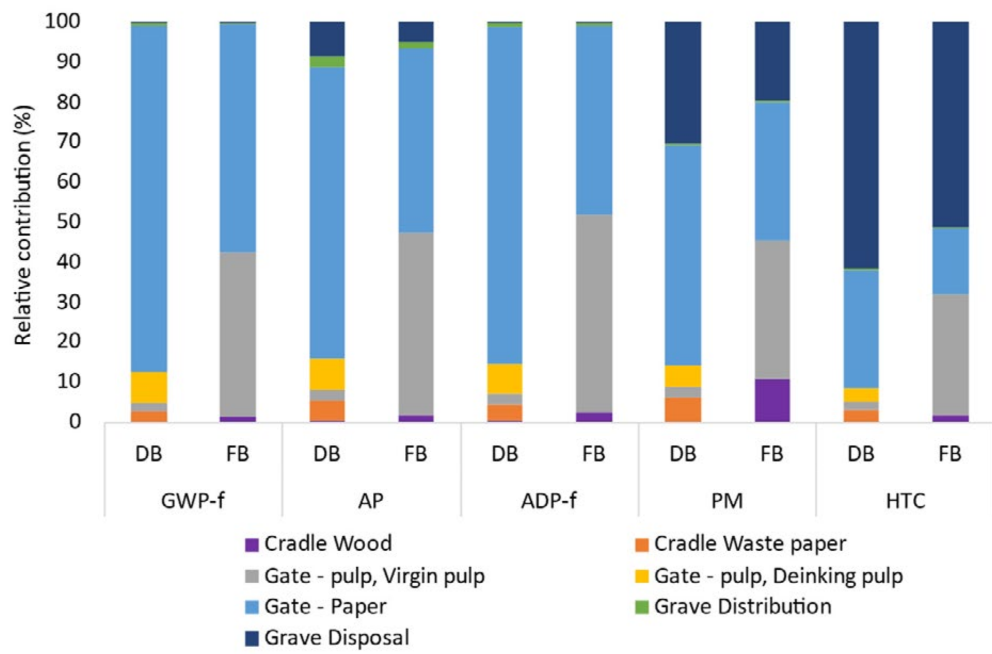

Fig. 5: Relative contribution of each stages on impact result of FB and DB paper production

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.

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

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.

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 $PM_{2.5}$ eq, respectively (Hong and Li, 2012). The ADP-f of writing paper for paper from virgin fiber and recycled fiber is 11,200 MJ and 6,480 MJ (Hong and Li, 2012). The HTC of the offset printing paper was 0.09E-06 CTUh (Silva *et al*., 2015). The impact contributions at each stage of the production process are shown in Fig. 5. GWP-fossil analysis at each stage shows that gate stage-paper production has the greatest impact, with 57% and 87% contributions to FB and DB products, respectively. The biggest process stage for acidification comes from the gate stage, paper production, contributing 46% and 73% for FB and DB products, respectively. The most significant stages of particulate impacts on DB paper products are found in paper production, contributing 55%, whereas pulp and paper production stages contribute to FB products, contributing 35% for each stage. The greatest impact on ADP-f for DB paper products was sourced from the paper production stage, contributing 84%, whereas FB products were sourced from the pulp and paper production stages, contributing 49% and 47%, respectively. The highest impact of HTC for DB and FB products was observed at the disposal stage.

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

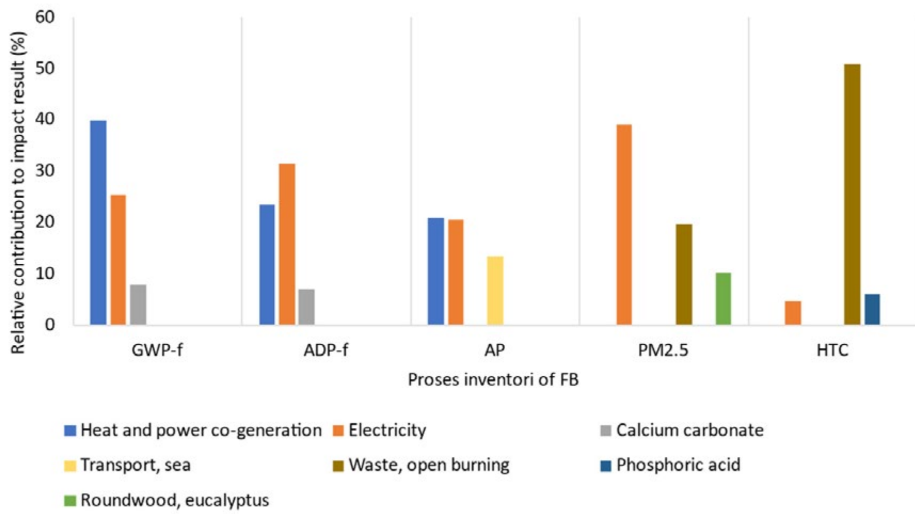

Fig. 6: Inventory contribution of FB product on life cycle impact result

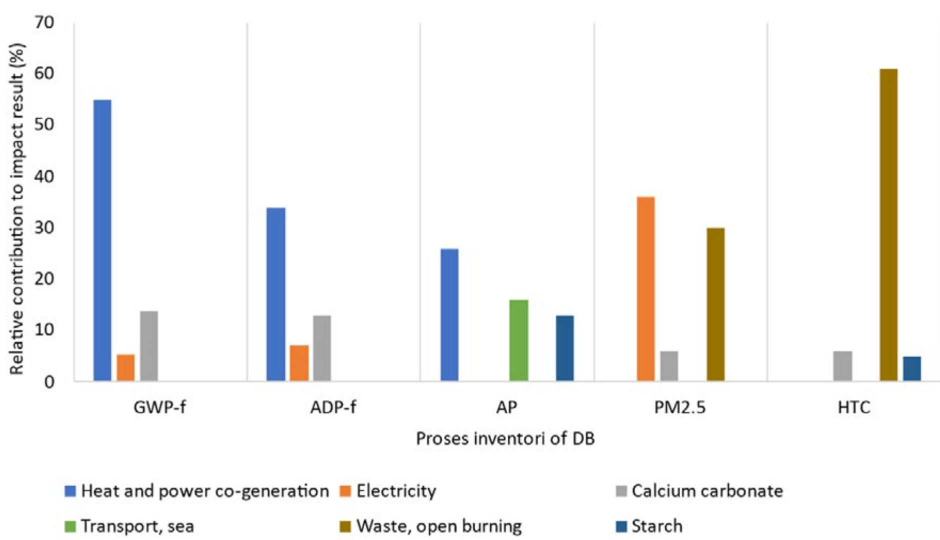

Fig. 7: Inventory contribution of DB product on life cycle impact result

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

REFERENCES

Ahamed, A.; Vallam, P.; Iyer, N.S.; Veksha, A.; Bobacka, J.; Lisak, G., (2021). Life cycle assessment of plastic grocery bags and their alternatives in cities with confined waste management structure: A Singapore case study. J Clean Prod., 278: 123956 **(11 pages).**

Akbari, M.Z.; Thepnuan, D.; Wiriya, W.; Janta, R.; Pansompong, P.; Hemwan, P.; Charoenpanyanet, A.; Chantara, S., (2021). Emission factors of metals bound with PM2.5 and ashes from biomass burning simulated in an open-system combustion chamber for estimation of open burning emissions. Atmos. Pollut. Res., 12(3): 13–24 **(12 pages).**

Alamsyah, D.P.; Othman, N.A.; Mohammed, H.A.A., (2020). The awareness of environmentally friendly products: The impact of green advertising and green brand image. Manage. Sci. Lett., 10(9): 1961–1968 **(8 pages).**

Bajpai, P., (2014). Introduction. Recycl. Deinking Recover. Pap., Elsevier Inc **(19 pages).**

Bajpai, P., (2015). Green chemistry and sustainability in pulp and paper industry. Green Chem. Sustainability Pulp Paper Ind., 1–258 **(258 pages).**

Bootdee, S.; Chantara, S.; Prapamontol, T., (2018). Indoor PM2.5 and its Polycyclic Aromatic Hydrocarbons in Relation with Incense Burning. IOP Conference Series. Earth Environ. Sci., 120(1): 0–8 **(8 pages).**

Brotosusilo, A.; Utari, D.; Negoro, H.A.; Firdaus, A.; Velentina, R.A., (2022). Community empowerment of waste management in the urban environment: More attention on waste issues through formal and informal educations. Global J. Environ. Sci. Manage., 8(2): 209-224 **(16 pages).**

BPS, (2021). Large and Medium Industry Quarterly Production Index. Badan Pusat Statistik or Statistic Indonesia.

Chang, S.S.; Lee, W.J.; Wang, L.C.; Lin, N.H.; Chang-Chien, G.P., (2013). Influence of the Southeast Asian biomass burnings on the atmospheric persistent organic pollutants observed at near sources and receptor site. Atmos. Environ., 78: 184–194 **(11 pages).**

Cheng, K.; Li, J.Y.; Wang, Y.; Ji, W.W.; Cao, Y., (2022). Characterization and risk assessment of airborne polycyclic aromatic hydrocarbons from open burning of municipal solid waste. Frontiers in Environ. Sci., 10: 1–10 **(10 pages).**

Fuente, T.; Athanassiadis, D.; González-García, S.; Nordfjell, T., (2017). Cradle-to-gate life cycle assessment of forest supply chains: Comparison of Canadian and Swedish case studies. J. Clean. Prod., 143: 866–881 **(16 pages).**

Drobyazko, S.; Skrypnyk, M.; Radionova, N.; Hryhorevska, O.; Matiukha, M., (2021). Enterprise energy supply system design management based on renewable energy sources. Global J. Environ. Sci. Manage., 7(3): 369-382 **(14 pages).**

Durdević, D.; Trstenjak, M.; Hulenić, I., (2020). Sewage sludge thermal treatment technology selection by utilizing the analytical hierarchy process. Water (Switzerland), 12(5): 0–16 **(16 pages).**

FAO, (2019). Global Forest Products 2018. For. Prod. Stat. Team For. Policy Resour. Div. FAO For. Dep.:20. Italy.

Gavrilescu, D.; Puitel, A. C.; Dutuc, G.; Craciun, G., (2012). Environmental impact of pulp and paper mills. Environ. Eng. Manage. J., 11(1): 81–86 **(6 pages).**

GGP, (2023). GreenHouse Gas Protocol.

Grossmann, H.; Handke, T.; Brenner, T., (2014). Paper recycling. Handbook of recycling: State-of-the-art for practitioners, Anal. Sci.: 165–178 **(14 pages).**

Hazbehiean, M.; Mokhtarian, N.; Hallajisani, A., (2022). Converting the cigarette butts into valuable products using the pyrolysis process. Global J. Environ. Sci.Manage., 8(1): 133-150 **(18 pages).**

Herrmann, I. T.; Moltesen, A., (2015). Does it matter which life cycle assessment (LCA) tool you choose? - A comparative assessment of SimaPro and GaBi. J. Clean. Prod., 86: 163–169 **(7 pages).**

Hong, J.; Li, X., (2012). Environmental assessment of recycled printing and writing paper: A case study in China. Waste Manage., 32(2): 264–270 **(7 pages).**

Huijbregts, M. A.J.; Breedveld, L.; Huppes, G.; De Koning, A.; Van Oers, L.; Suh, S., (2003). Normalisation figures for environmental life-cycle assessment: The Netherlands (1997/1998), Western Europe (1995) and the world (1990 and 1995). J. Clean. Prod., 11(7): 737–748 **(12 pages).**

Humbert, S.; Marshall, J.D.; Shaked, S.; Spadaro, J.V.; Nishioka, Y.; Preiss, P.; McKone, T.E.; Horvath, A.; Jolliet, O., (2011). Intake fraction for particulate matter: Recommendations for life cycle impact assessment. Environ. Sci. Technol., 45(11): 4808–4816 **(9 pages).**

IPCC, (2023). The Intergovernmental Panel on Climate Change. Sixth Assessment Report.

Kameni Nematchoua, M., (2022). Strategies for studying acidification and eutrophication potentials, a case study of 150 countries. J, 5(1): 150–165 **(16 pages).**

Kinnarinen, T.; Golmaei, M.; Jernström, E.; Häkkinen, A., (2016). Separation, treatment and utilization of inorganic residues of chemical pulp mills. J. Clean. Prod. Elsevier Ltd **(12 pages).**

Klöpffer, W., (2012). The critical review of life cycle assessment studies according to ISO 14040 and 14044. Int. J. Life Cycle Assess., 17(9): 1087–1093 **(7 pages).**

Kusumawati, D.I.; Mangkoedihardjo, S., (2021). Promising approach for composting disposable diapers enhanced by Cyanobacteria. Global J. Environ. Sci. Manage., 7(3): 439-456 **(18 pages).**

Laurijssen, J.; Faaij, A.; Worrell, E., (2013). Benchmarking energy use in the paper industry: A benchmarking study on process unit level. Energy Effic., 6(1): 49–63 **(15 pages).**

Le Dinh, C.; Fujiwara, T.; Asari, M.; Bao, N.D; Song Toan, P.P., (2022). Optimization of solid waste collection system in a tourism destination. Global J. Environ. Sci. Manage., 8(3): 419-436 **(18 pages).**

Malahayati, M.; Masui, T., (2021). Potential impact of introducing emission mitigation policies in Indonesia: how much will Indonesia have to spend? Mitig. Adapt. Strateg. Global Chang. 26: 37 **(37 pages).**

Man, Y.; Han, Y.; Li, J.; Hong, M.; Zheng, W., (2019). Life cycle energy consumption analysis and green manufacture evolution for the papermaking industry in China. Green Chem., 21(5): 1011–1020 **(12 pages).**

Maphosa, M.; Maphosa, V. (2022). A bibliometric analysis of the effects of electronic waste on the environment. Global J. Environ. Sci.Manage., 8(4): 589-606 **(18 pages).**

Moghadam, H.; Samimi, M., (2022). Effect of condenser geometrical feature on evacuated tube collector basin solar still performance: Productivity optimization using a Box-Behnken design model. Desalination, 542: 116092 **(8 pages).**

Nimesha, S.; Hewawasam, C.; Jayasanka, D.J.; Murakami, Y.; Araki, N.; Maharjan, N. (2022). Effectiveness of natural coagulants in water and wastewater treatment. Global J. Environ. Sci. Manage., 8(1): 101-116 **(16 pages).**

Ozola, Z. U.; Vesere, R.; Kalnins, S.N.; Blumberga, D., (2019). Paper Waste Recycling. Circular Economy Aspects. Environ. Clim. Technol., 23(3): 260–273 **(14 pages).**

Pryshlakivsky, J.; Searcy, C., (2013). Fifteen years of ISO 14040: a review. J. Clean. Prod., 57: 115–123 **(9 pages).**

Rewlay-ngoen, C.; Papong, S.; Sampattagul, S., (2014). The NPP and social asset impacts of acidification from coal-fired power plant in Thailand. Energy Procedia. 52: 234–241 **(8 pages).**

Rosenbaum, R.K.; Bachmann, T.M.; Gold, L. S.; Huijbregts, M.A.J.; Jolliet, O.; Juraske, R.; Koehler, A.; Larsen, H.F.; MacLeod, M.; Margni, M.; McKone, T.E.; Payet, J.; Schuhmacher, M.; Van De Meent, D.; Hauschild, M.Z., (2008). USEtox - The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int. J. Life Cycle Assess., 13(7): 532–546 **(15 pages).**

Santos, A.; Barbosa-Póvoa, A.; Carvalho, A., (2018). Life cycle assessment of pulp and paper production – A Portuguese case study. In Computer Aided Chemical Engineering. Vol. 43. Elsevier Masson SAS **(6 pages).**

Schau, E.M., (2019). Product Environmental Footprint (PEF) Category Rules (PEFCR) for intermediate paper products – Overview and discussion of important choices made in the development. In I. Karlovits (Ed.). Pulp and Paper Institute. Proceedings of the 1st International Conference on Circular Packaging Proceeding International Conference. CPC., 175–184 **(10 pages).**

Schulte, M.; Hammar, T.; Stendahl, J.; Seleborg, M.; Hansson, P.A., (2021). Time dynamic climate impacts of a eucalyptus pulp product: Life cycle assessment including biogenic carbon and substitution effects. GCB Bioenergy. 13(11): 1831–1850 **(20 pages).**

Silva, D.A.L.; Raymundo Pavan, A.L.; Augusto De Oliveira, J.; Ometto, A.R., (2015). Life cycle assessment of offset paper production in Brazil: Hotspots and cleaner production alternatives. J. Clean. Prod., 93: 222–233 **(12 pages).**

Simão, L.; Hotza, D.; Raupp-Pereira, F.; Labrincha, J.A.; Montedo, O.R.K., (2018). Wastes from pulp and paper mills - A review of generation and recycling alternatives. Ceramica. 64(371): 443–453 **(11 pages).**

Sivakumar, D.; Srikanth, P.; Ramteke, P.W.; Nouri, J., (2022). Agricultural waste management generated by agro-based industries using biotechnology tools. Global J. Environ. Sci. Manage., 8(2): 281-296 **(16 pages).**

Song, K.; Zhu, X.; Zhu, W.; Li, X., (2019). Preparation and characterization of cellulose nanocrystal extracted from Calotropis procera biomass. Bioresour. Bioprocess. 6(1) **(8 pages).**

SIPSN, (2020). National waste management information system. Ministry of Environment and Forestry of Indonesia.

Suroso, D.S.A.; Setiawan, B.; Pradono, P.; Iskandar, Z.S.; Hastari, M.A., (2022). Revisiting the role of international climate finance (ICF) towards achieving the nationally determined contribution (NDC) target: A case study of the Indonesian energy sector. Environ. Sci. Policy. 131: 188–195 **(8 pages).**

van Oers, L.; Guinée, J., (2016). The abiotic depletion potential: Background, updates, and future. Resources, 5(1) **(12 pages).**

Wang, Y.; Cheng, K.; Wu, W.; Tian, H.; Yi, P.; Zhi, G.; Fan, J.; Liu, S., (2017). Atmospheric emissions of typical toxic heavy metals from open burning of municipal solid waste in China. Atmos. Environ., 152: 6–15 **(10 pages).**

WBCSD, (2015). World business council for sustainable development, forest solutions group. 2015. Facts and trends: fresh and recycled fiber complementarity, New York.

WEF, (2016). Design and Management for Circularity – the Case of Paper. The World Economic Forum. 91-93 route de la Capite CH-1223 Cologny/Geneva, Switzerland.

Yi, Y.; Wang, Z.; Wennersten, R.; Sun, Q., (2017). Life cycle assessment of delivery packages in china. Energy Procedia, 105: 3711–3719 **(9 pages).**

You, S.; Neoh, K.G.; Tong, Y.W.; Dai, Y.; Wang, C.H., (2017). Variation of household electricity consumption and potential impact of outdoor PM2.5 concentration: A comparison between Singapore and Shanghai. Appl. Energy, 188: 475–484 **(10 pages).**

Zhang, N.; Huang, H.; Duan, X.; Zhao, J.; Su, B., (2018). Quantitative association analysis between PM2.5 concentration and factors on industry, energy, agriculture, and transportation. Sci. Rep., 8(1): 1–9 **(9 pages).**

Zhao, Q.; Ding, S.; Wen, Z.; Toppinen, A., (2019). Energy flows and carbon footprint in the forestry-pulp and paper industry. Forests. 10(9) **(23 pages).**

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