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Research Article

Mitigation potential for improving the life cycle of plastic products in indonesia

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Abstract

The widespread use of plastic products in society has been proven to have severe impacts, such as global warming and other toxic impacts. Life cycle improvement can reduce the environmental impact of manufactured products. Life cycle improvement is an effort to reduce the amount and quality of emissions generated from raw material extraction to post-use product disposal. Mitigation efforts to improve the life cycle of manufactured products can contribute to achieving the Sustainable Development Goals (SDGs). This study aims to qualitatively find the potential for mitigating improvements to the life cycle of Indonesian plastic products using the Life Cycle Engineering (LCE) approach. Product life cycle hotspot data was identified from a review of 21 selected articles containing the results of the Life Cycle Assessment (LCA) study of Indonesian plastic products through the Systematic Literature Review (SLR). The life cycle of plastic products can be improved by tracking hotspot causes and finding mitigation options in an integrated manner. The life cycle of Indonesian plastic products analyzed can be identified in life cycle components: collection, shredding, raw materials, transportation, pelletizing, production, packaging, distribution, end-of-life (EOL) handling, and production avoidance. The results show that hotspot causes include the nature of plastic raw materials, electricity use, fuel oil use, and unmanaged plastic waste. The potential for mitigation of improving the life cycle of Indonesian plastic products is identified in 16 options in five groups, namely: changing raw materials, efficiency of electricity use, efficiency of fuel use, improvement of plastic waste handling, and demand control.

Keywords:
Improvement of plastic product life cycle;
Life Cycle Engineering;
Hotspot Causes;
Mitigation Potential

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1. Introduction

Plastic is a polymer material with many advantages and uses, and it is increasingly widespread in various fields. As a manufactured product, plastic products also have the potential to cause severe environmental impacts throughout their life cycle. Improving the environmental performance of plastic products throughout their life cycle is needed to make their use more sustainable. In general, various methods can be used to improve the ecological performance of manufactured products; (Wenzel et al., 1994) mention that there are five strategies for improving environmental performance: (1) better material handling, (2) saving or replacing chemicals, (3) saving thermal energy, (4) saving electricity, and (5) reducing overhead. Implementing these environmental performance improvement strategies into the actual phase requires engineering design from a life cycle perspective. Design strategies in the life cycle include the following phases: pre-manufacturing, manufacturing, transportation/distribution, use, and disposal (Alting, 1995). An integrated approach that considers environmental, economic, and social aspects in developing design, manufacturing processes, and products can be carried out through the LCE approach (Jeswiet, 2003). LCE can contribute to achieving the 12 SDGs, especially by implementing sustainable production and consumption. Several LCE experts have discussed how LCE can contribute to meeting the SDGs. The discussion at the LCE expert meeting was continued with related research, including eco-innovation strategies in manufacturing (Janahi et al., 2021), and the eco-design learning framework on the integration of life cycle assessment in engineering learning for sustainable competency improvement (Deng et al., 2021). Due to differences in product usage, personalization, and software or hardware updates, the life cycle paths of each product of the same product type will be increasingly different.

Setiastuti has reviewed the potential role of the LCA of plastic products in achieving SDGs. In Indonesia, developing plastic products into sustainable products is necessary. Research development can be continued through the operationalization approach of the LCE concept. The study aims to identify potential mitigations for improving the life cycle of Indonesian plastic products based on the LCE approach qualitatively. This approach can formulate potential mitigations and serve as a guideline for developing sustainable plastic products (Setiastuti et al., 2023).

2. Method

A qualitative descriptive approach will be used to analyze the problems (hotspots) resulting from mapping LCA studies of Indonesian plastic products and then identify improvement solutions based on the LCE perspective. Hotspot mapping LCE content search and engineering solution use SLR. The research process framework can be seen in Figure 1.

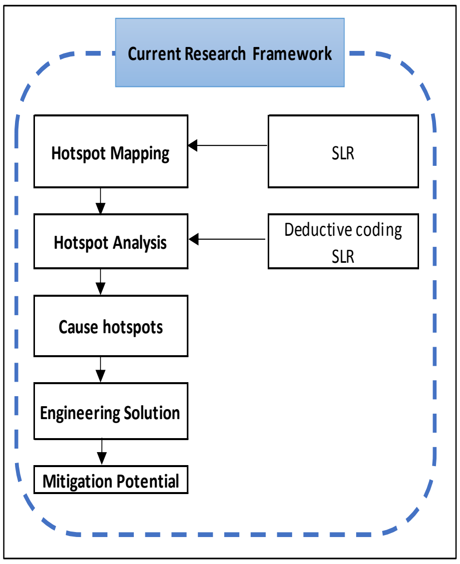

Fig. 1. Research Framework Scheme
Source: Modification (Kara et al., 2023)

2.1. Procedures for selecting for the Systematic Literature Review in this research

The article search was conducted in 2 ways: identifying articles reviewed by Setiastuti (2023) and searching for additional articles from the Scopus database. The number of articles reviewed by Setiastuti (2023) is 27. Additional articles used the keywords "plastic life cycle assessment", "life cycle assessment polystyrene", "life cycle assessment polyethylene", "life cycle assessment polyester", "life cycle assessment polypropylene", "life cycle assessment in Indonesia", "life cycle assessment of plastic", and 1,523 articles were found, the research protocol in figure 2. The additional articles are limited to publications published from 2022 to 2025. This is to update (Setiastuti et al., 2023) database. The inclusion and exclusion criteria of the collected articles are in Table 1.

Table 1
Inclusion and exclusion criteria

No.	Inclusion	Exclusion
1	LCA calculations are carried out for plastic products in Indonesia	Article in press
2	Articles are in Indonesian and English	Articles without full text
3		Articles that do not give information about hotspots
4		Articles that require citation permission

The selected articles are LCA calculations carried out for plastic products in Indonesia. They are in Indonesian and English. The articles not selected are articles in press, articles without full text, articles that do not provide information about hotspots, and articles that require citation permission. The total number of articles reviewed in this research is 21. The results of the article selection can be seen in Table 2.

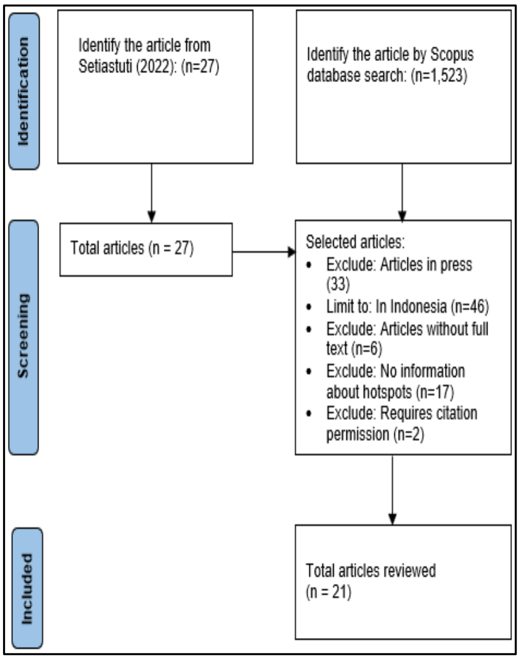

Fig. 2. Research Prism Protocol

2.2. Research gap

While Setiastuti (2023) has reviewed the potential role of LCA for plastic products in achieving SDGs in Indonesia, and other studies have examined eco-innovation strategies and eco-design learning frameworks (Janahi et al., 2021; Deng et al., 2021). There is a lack of comprehensive operationalization of the LCE concept tailored explicitly to the context of Indonesian plastic products. Prior research identifies hotspots in the life cycle of these products, such as the use of specific plastics, electricity consumption in thermoforming, fuel usage, unmanaged waste, and the causes of hotspots. However, a systematic framework is needed to translate these hotspot analyses into concrete, prioritized mitigation strategies and product engineering solutions to improve Indonesian plastic products' life cycle performance. Specifically, there is a need to investigate and formulate potential mitigations, distinguishing between foreground and background systems, to provide clear guidelines for developing more sustainable plastic products in Indonesia.

2.3. LCE Approach to Improving Life Cycle Performance

LCE is defined as engineering activities to create products by applying technological and scientific principles, maintaining environmental protection and resource conservation, paying attention to the principles of sustainability, and improving the economy and social awareness through optimizing the product life cycle and minimizing pollution and waste (kellens, 2018). LCE targets product development and manufacturing from a life cycle perspective and aims to create more sustainable solutions. In this case, the environmental aspect is the basis of the LCE approach (Jamwal et al., 2021). LCE objects include raw material extraction activities, product development from reuse, remanufacturing, and recycling to disposal, as well as engineering and after-sales services (Jamwal et al., 2021). The life cycle phases in LCE design include a systematic "cradle to grave" process, with engineering objects of goods and services having a complete environmental profile (Hauschild et al., 2020).

The LCE method of working based on the results of the LCA study allows for precise identification of the causes of problems (hotspots) in process components throughout the life cycle so that impact treatment can be carried out on the proper objects (Hauschild et al., 2020). Significant improvements can be achieved if environmental performance and consideration of the entire product life cycle can be identified early on. In this case, product characteristics and product usage patterns must be known. Reasons for developing products with an LCE approach include reducing material use, extending the product life cycle, extending the material life cycle, product improvement, and product management. The improvement process can be achieved by reducing energy consumption, using additional equipment, and improving infrastructure. Furthermore, to evaluate product development, environmental impact improvements must be carried out routinely (Lundquist, 2002).

Kara, S. describes LCE's operational approach to improving life cycle performance through six steps: determining the scope, conducting a life cycle assessment to identify hotspots, finding engineering solutions according to the targets in the scope, determining relevant priorities that cause impacts, formulating mitigation strategies, and carrying out product engineering according to the selected mitigation strategy (Kara et al., 2023).

In this study, the LCE approach to improve the life cycle of plastic products is carried out by mapping hotspots from various cases of Indonesian plastic products, analyzing hotspots to determine their position and causes in their life cycle, seeking engineering solutions, and finding potential mitigation for improving the life cycle of plastic products in general, which will be discussed in the next sub-chapter.

2.4. Formulation of Mitigation Potential

The formulation of mitigation potential for improving the life cycle of plastic products using the LCE principle follows the steps shown in Figure 1. Hotspot mapping is the starting point for identifying environmental impacts, and it is carried out by plotting the hotspot positions of the LCA study results in a hotspot map. Based on the review of the LCA study results, the causes of the hotspots and their technical solutions are known. The technical solution is also strengthened by the results of other scientific research related to the technical solution. Mitigation potentials, which are technical solutions, are grouped into two entities: foreground and background systems. The background system consists of processes not influenced (independent) by the product and its engineering (for example, energy, natural resources, and the environment). In contrast, the foreground system is the physical product along with its stages of use, other processes, and the life cycle that is influenced by decisions made in engineering. This division will make it easier to place technical solutions; if the hotspot is on the background entity, the technical solution is carried out through engineering on the foreground side. Mitigation can also be done by reducing the demand for the product to reduce the total impact caused. Demand is derived from the population "P" from the total impact identity formula (Kara et al., 2023).

3. Result and Discussion

3.1. Indonesian Plastic Products

Plastic products have become part of everyday life because of their various applications, low cost, durability, light weight, and flexibility. Plastic products used in Indonesia include consumer goods and capital goods, which include automotive components, medical devices, household appliances, electronic equipment, pipes, and equipment. Non-electric plastic goods include various bottles and packaging, plastic bags, straws, sachet packaging, medical and sports equipment, clothing, sanitation equipment, garden and agricultural equipment, beauty tools, and plastic ore. Plastic products and production equipment that are the objects of study include Automotive filters, plastic waste, plastic ore, plastic packaging, plastic waste recycling, extruders, plastic straws, plastic cups, drinking water bottles, packaging products, Back sheet Diapers, Battery Containers, molding processes, plastic bags, plastic containers, and Polyethylene terephthalate (PET) Flakes.

Table 2
Source of life assessment data of Indonesian plastic products

No.	Life Cycle Assessment theme	Reference
1	LCA and energy efficiency on plastic waste recycling;	(Rosmiati & Hadiyanto, 2020)
2	LCA in the plastic waste recycling supply chain	(Sirait, 2017)
3	LCA of Plastic Components in the Production of Automotive Filters	(Sutanto & Rumende, 2022)
4	LCA on flexible plastic packaging	(Irzalinda & Ardi, 2020)
5	LCA on extruder process	(Ningrum & Afiuddin, 2018)
6	LCA in the polystyrene cup manufacturing process	(Khairona, 2019)
7	LCA of bottled water production processes	(Evangelista, 2019)
8	LCA in back sheet diaper products	(Mutiara, 2018)
9	LCA on the battery container	(Laurence & Kasena, 2018)
10	LCA on plastic recycling	(Ilhamdika, 2017)
11	LCA on injection molding machines in processing polypropylene	(S. Y. Saputra & Hanafi, 2017)
12	LCA on polyester yarn production	(Utami et al., 2015)
13	LCA for sustainability packaging analysis	(Yola, 2013)
14	LCA of Plastic Waste End-of-Life for India and Indonesia	(Neo et al., 2021)
15	LCA on Jakarta's Plastic Waste	(Tiogana, 2020)
16	LCA PET drinking bottle	(Ibnu, 2019)
17	LCA on packaging products made from polystyrene foam	(Noya, 2018)
18	LCA on Plastic Jerry Cans (comparative study)	(A. Saputra et al., 2023)
19	LCA on Plastic Waste Recycling	(Puspita et al., 2022)
20	LCA on Multilayer Plastic-Metallized Packaging	(Sinaga et al., 2023)
21	LCA on PET Flakes	(Rahman & Gandasasmita, 2024)

Based on data from the Ministry of Industry of Indonesia, the most extensive use of plastic in Indonesia is in the food and beverage industry, with PET, Polyethylene (PE), and Polypropylene (PP). Some advantages of plastic properties are that it is light, flexible, able to protect materials from contamination, and low cost, making plastic widely used, especially for packaging (Ministry of Environment and Forestry of the Republic of Indonesia, 2019).

3.2. Mapping of Indonesian Plastic Products' Life Cycle Hotspots

A hotspot is a point in a life cycle process with the highest emission impact value compared to other impact-producing processes within the LCA boundary (Ningrum & Afiuddin, 2018). Hotspots are identified from the results of LCA analysis of products in certain weight or volume units. SLR produces hotspot findings, hotspot causes, and indications for life cycle improvement solutions. In this study, hotspots are divided into two categories: major hotspots, which have the highest values, and minor hotspots, which have lower values. The results of the life cycle hotspot mapping of Indonesian plastic products can be seen in Figure 3.

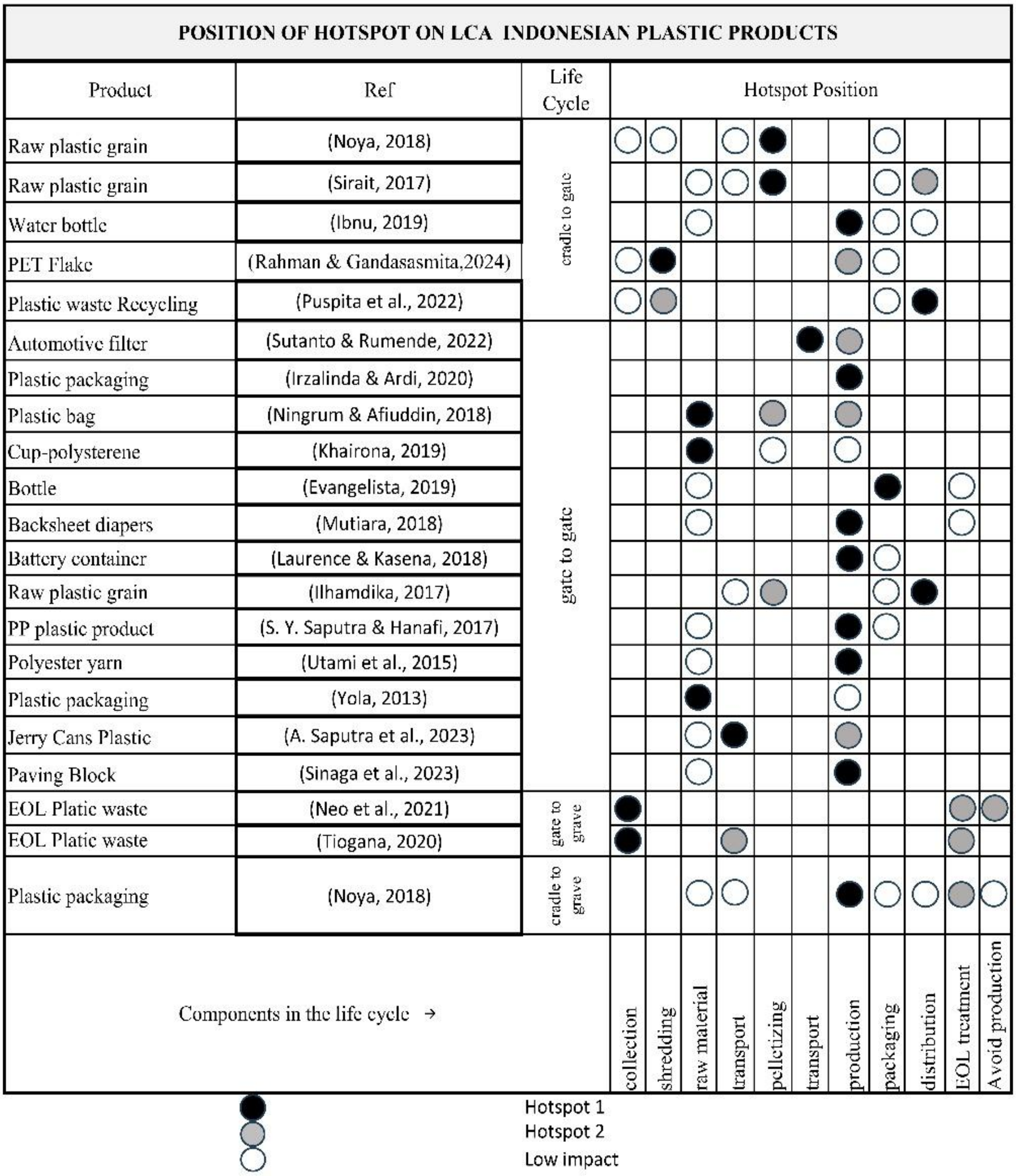

Fig. 3. Hotspot Map of the Indonesian Plastic Products

The cradle-to-gate recycling life cycle group comprises plastic product production activities: Raw plastic grain, Water bottles, Plastic waste recycling, and PET flakes. The gate-to-gate life cycle group comprises automotive filters, plastic packaging, plastic bags, cups, bottles, bag sheet diapers, battery containers, raw plastic grain, polyester yarn, water bottles, and paving blocks. The gate-to-grave life cycle group consists of EOL plastic waste. The cradle-to-grave life cycle group consists of one plastic packaging production activity. The most considerable emission impacts that become major (1) and minor (2) hotspots in the life cycle include 27 midpoint and endpoint categories.

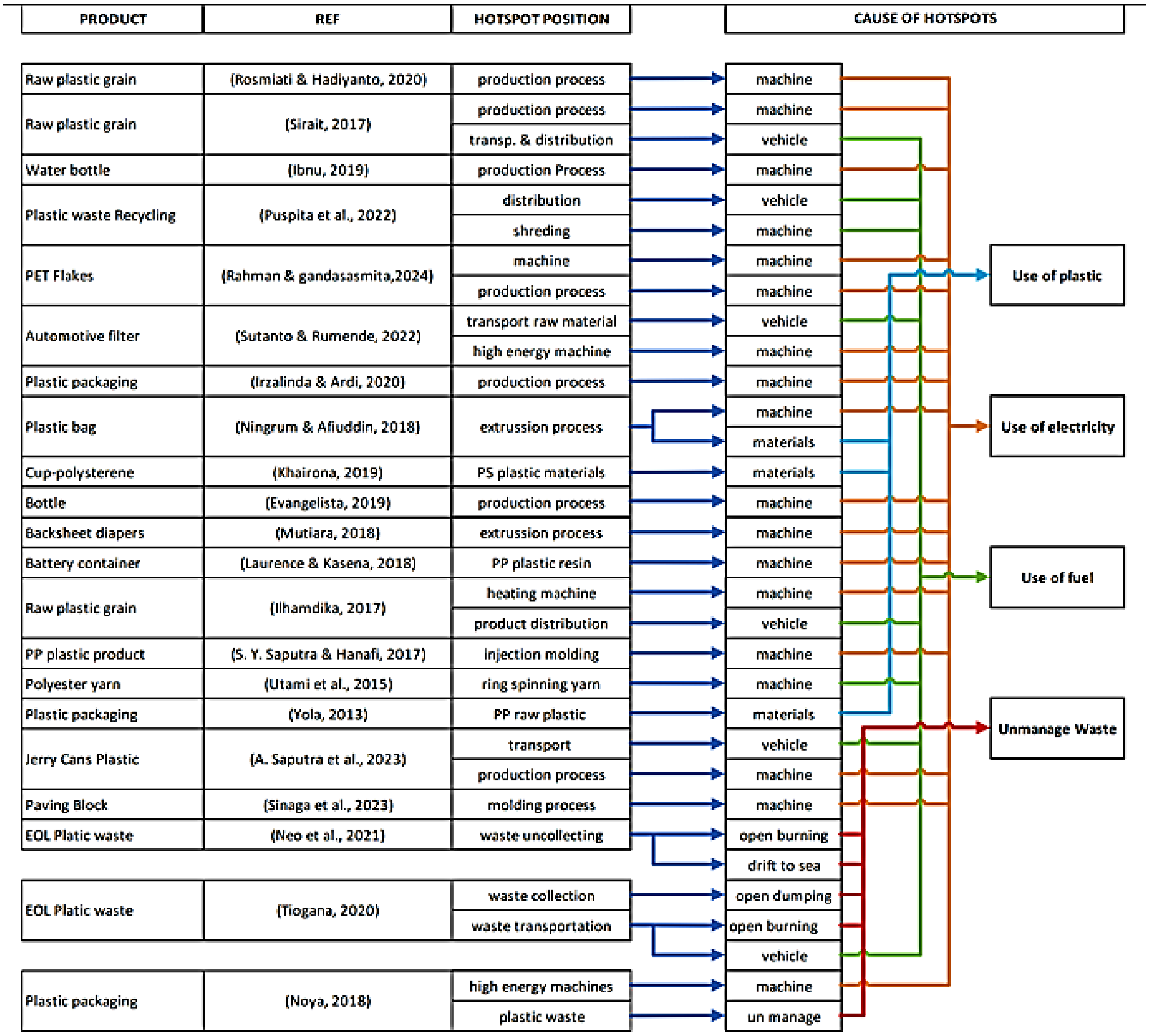

Fig. 4. Analysis of Hotspot Causes

3.3. Hotspots Analysis

Hotspot analysis was conducted to determine the cause of hotspots, which were identified from the review of major and minor emission-producing process components in the product life cycle. Through deductive coding tracing, four main components of input and processes causing hotspots were identified in the studied objects, including the use of plastic, electricity, fuel, and unmanaged waste. Details of the analysis can be seen in Figure 4.

IMPACT OF HOTSPOT ON LCA INDONESIAN PLASTIC PRODUCTS

Product	Ref	Hots pot	Life Cycle	Impact																													
Raw plastic grain	(Rosmiati & Hadiyanto, 2020)	1	cradle to gate							E								E		E													
Raw plastic grain	(Sirait, 2017)	1								E																							
		2								F																							
Water bottle	(Ibnu, 2019)	1					E												E														
Plastic Waste Recycling	(Puspita et al., 2022)	1								F				F																			
		2								E				E																			
PET Flakes	(Rahman & Gandasasmita,2024)	1								E				E	E									E									
		2								E				E	E									E									
Automotive filter	(Sutanto & Rumende, 2022)	1	gate to gate																												F		F
		2																														E	E
Plastic packaging	(Irzalinda & Ardi, 2020)	1								E												E	E										
Plastic bag	(Ningrum & Afiuddin, 2018)	1			E																			E									
		2								E														E									
		3							P																								
Cup-polysterene	(Khairona, 2019)	1								P														P	P	P				P			
Bottle	(Evangelista, 2019)	1					E		E	E																							
Backsheet diapers	(Mutiara, 2018)	1																			E		E						E				
Battery container	(Laurence & Kasona, 2018)	1								E												E	E										
Raw plastic grain	(Ilhamdika, 2017)	1					E																										
		2																						F									
PP plastic product	(S. Y. Saputra & Hanafi, 2017)	1											E	E					E														
Polyester yarn	(Utami et al., 2015)	1								E																							
Plastic packaging	(Yola, 2013)	1								P								P			P	P							P				
Jerry Cans Plastic	(A. Saputra et al., 2023)	1							F	F			F	F										F									
		2							E	E			E	E										E									
Paving Block	(Sinaga et al., 2023)	1							E	E			E	E		E								E									
EOL Platic waste	(Neo et al., 2021)	1	gate to grave					W		W										W							W	W					
		2		W								W					W		W									W					
		3		W								W					W		W									W					
EOL Platic waste	(Tiogana, 2020)	1						W		W										W							W	W					
		2							F	F			F	F										F									
		3		W								W					W		W									W					
Plastic packaging	(Noya, 2018)	1	cradle to grave							E										E													
		2		W																													
Calculation Methods	ReCIPe 2016			v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v						v	v			v	v	v
	EDIP 2003				v		v	v	v	v			v			v								v	v	v				v			
	Eco-Indicator 99					v	v			v			v	v		v	v	v	v	v			v	v	v	v			v				
	Impact 2002+																					v											
Mid Point / Endpoint Impact Category				Particulate Matter	H.Ozone Formation (hum)	Ionizing Radiation	Stratos Ozone depletion	Human Toxicity (cancer)	Human Toxicity (non canc)	Global Warming	Water Use	Water Depletion	Freshwater ecotoxicoty	Freshwater Eutropication	Trop.Ozone (eco)	Terestrial ecotoxicity	Terestrial Acidification	Land use (transformation)	Marine ecotoxicity	Fosil Depletion	Fosil Resources	Non renewable energy	Respiratory Inorganic	Acidification	Terestrial Eutriphication	Aquatic eutrophicatin	Cumulativ Energy Demand	Urban Land Occupation	Carcinogen	IHHM	Human Health (endpoint)	Ecosystem (endpoint)	Resources (endpoint)

Caption:
Q: Impact of Plastic Use
E: Impact of Electricity Usage
F: Impact of Fuel Use
W: The Impact of Unmanaged Waste

Fig. 5. Map of hotspot impacts on LCA results of Indonesian plastic product

The four categories of hotspot causes above can be explained as follows:

1. Use of plastic: Plastic consists of various types with different characteristics; plastic comes from resin produced from petroleum, which is converted into plastic products through a thermoforming process. The cause of hotspots is the thermoforming process, type, and nature of plastic. The thermoforming process of plastic directly impacts the environment (Khairona, 2019). Certain types of plastic, such as PET (Yani & Warsiki, 2013), plastic waste (Neo et al., 2021), polyethylene low-density granulate (PE-LLD) (Mutiara, 2018), Polystyrene (PS), PP (Neo et al., 2021), (A. Saputra et al., 2023), (Jamwal et al., 2021), plastic recycling (Evangelista, 2019) causes greenhouse gas (GHG) impacts of varying magnitudes.
   According to the impact map in Figure 5, the impacts of emissions caused by the use of plastic are Human Toxicity (noncancer), Global Warming, Land use (transformation), Fossil Resources, Nonrenewable Energy, Acidification, Terrestrial Eutrophication, Aquatic Eutrophication, Cancer, and Impact on Human Health and Materials (IHHM).
   Findings from several cases that need to be noted are that 1 kilogram of Polypropylene plastic material in the production of plastic sacks (Ningrum & Afiuddin, 2018) can cause an impact on Ozone Formation (human) of 0.01734 m^2ppmh, Global Warming of 2.6 $kgCO_2$-eq, Acidification of 0.107 m^2, and Human toxicity of air of 0.085 people. In the case of plastic cup production (Khairona, 2019), 1 kilogram of PS plastic material can cause an Acidification Potential impact of 0.1618 m^2UES, Global warming of 3.3443 $kgCO_2$-eq, IHHM of 0.0011 pers*ppm*hour, Terrestrial Eutrophication of 0.1215 m^2UES, Aquatic Eutrophication of 0.0039 $kgNO_2$-eqThe impact of emissions caused by electricity use is Terrestrial Ozone Formation (human), Ozone Depletion, Human Toxicity (non-cancer), Global Warming, Water Use, Freshwater Ecotoxicity, Freshwater Eutrophication, Tropical Ozone (eco), Terrestrial Ecotoxicity, Terrestrial Acidification, Land use (transformation), Marine Ecotoxicity, Fossil Depletion, Fossil Resources, Non-Renewable Energy, Respiratory Inorganic, Acidification, Carcinogen.
2. Use of electricity: Electricity is a thermal energy source and driving force for shredding and production machines. The amount of emissions is influenced by the type of plastic, the type and performance of the machine, and the source of generating energy (coal and fuel) The cause of hotspots is that the thermoforming process requires large amounts of energy (Ilhamdika, 2017). Some types of plastic also require a greater electrical energy intake, such as PE LLD (Mutiara, 2018) and PS foam (Noya, 2018). The operation of production machines requires electrical energy, such as injection molding machines (Sutanto & Rumende, 2022), extruders (Mutiara, 2018; Ningrum & Afiuddin, 2018; Rosmiati & Hadiyanto, 2020; Noya, 2018; Setiastuti et al., 2023; A. Saputra et al., 2023; Sinaga et al., 2023); shredding machine (Rosmiati & Hadiyanto, 2020),

(Rahman & Gandasasmita, 2024). Electrical energy is also used to drive other production machines, such as belt conveyors (Evangelista, 2019; Ibnu, 2019). Ring spinning in polyester yarn production (Utami et al., 2015), and absorption chiller machine (Ibnu, 2019). The age of the machine also affects the efficiency of energy use (S. Y. Saputra & Hanafi, 2017). The power generation energy sources used in the production process, such as Diesel Power Generation (Rosmiati & Hadiyanto, 2020), Coal-fired Power Plants (Laurence & Kasena, 2018; Ilhamdika, 2017; Sirait, 2017; Neo et al., 2021; Irzalinda & Ardi, 2020; Ningrum & Afiuddin, 2018), and energy sources whose type is not mentioned (Evangelista, 2019; A. Saputra et al., 2023; Utami et al., 2015), causes significant emission impacts with varying numbers.

The impact of emissions caused by electricity use is Terrestrial Ozone Formation (human), Ozone Depletion, Human Toxicity (non-cancer), Global Warming, Water Use, Freshwater Ecotoxicity, Freshwater Eutrophication, Tropical Ozone (eco), Terrestrial Ecotoxicity, Terrestrial Acidification, Land use (transformation), Marine Ecotoxicity, Fossil Depletion, Fossil Resources, Non-Renewable Energy, Respiratory Inorganic, Acidification, Carcinogen. The generation of GHG emissions per kWh of electricity from several plastic product production equipment identified from various references can be seen in Table 2.

Table 3
GHG emissions generation from 1 kWh of electricity used in various equipment

No	Equipment	Reference	GHG $KgCO_2/kWh$
1	Extruder Machine	(Khairona, 2019)	4.6253
2	Plastic Roll Machine	(Laurence & Kasena, 2018)	2.0923
3	Mineral Water Filling Machine	(Laurence & Kasena, 2018)	2.5520
4	Plastic Granules Extruder	(Ilhamdika, 2017)	4.7544
5	Refrigeration Machine	(Ilhamdika, 2017)	4.7550
6	Cutting Machine	(Ilhamdika, 2017)	4.7500

Meanwhile, according to the calculator United States Environmental Protection Agency (USEPA) calculations, 1 kWh of electricity generated by burning coal equals GHG emissions of 0.4165 $kgCO_2$-eq.

3. Use of Fuel: Fuel is used for transportation and distribution vehicles, diesel engine drivers, shredding and extruder drivers, and power-generating machines (Noya, 2018; Sinaga et al., 2023; Sirait, 2017). Transportation consists of the transportation of raw materials for production input (Irzalinda & Ardi, 2020; Puspita et al., 2022), product distribution to agents or consumers (Noya, 2018; Puspita et al., 2022; Tiogana, 2020), and transportation of waste from Temporary Disposal Site to landfills (Tiogana, 2020). The cause of hotspots is the use of fossil fuels (diesel) from transportation equipment, shredding machines, extruders, and generators (Rosmiati & Hadiyanto, 2020), which produces high GHG emissions. The impacts of emissions caused by fuel use are Particulate Matter, TR. Ozone Formation (hum), Ionizing Radiation, Ozone Depletion, Human Toxicity (cancer), Human Toxicity (non-cancer), Freshwater Ecotoxicity, Freshwater Eutrophication, Acidification.
   GHG emission generation is achieved by using 1 liter of fuel (diesel) in the product distribution process case (Sirait, 2017) of 11,281 kg CO_2-eq and in the raw material transportation process of 12,857 kg CO_2-eq. Other sources in different units (tons per kilometer) (Tiogana, 2020) were identified in the raw material transportation process of 1.881 $kgCO_2$-eq/tkm. The finished product distribution process of 0.399 kg CO_2-eq/tkm. Meanwhile, based on the Conversion USEPA, 1 liter of diesel equals GHG emissions of 2,690 kg CO_2-eq.
4. Unmanaged Waste: Waste managers are formal and non-formal institutions; the cause of hotspots is the presence of high carbon plastic waste (PP, PE), open dumping in waste disposal, and non-recycled plastic waste is only collected (collection) 39% (Neo et al., 2021), the distance to the landfill is too far (Tiogana, 2020), and the behavior of plastic users at the end of the cycle (Mutiara, 2018; Khairona, 2019; Noya, 2018; Neo et al., 2021). The impacts of emissions caused by current plastic waste management are Human Toxicity, Global Warming, Fossil Depletion, Cumulative Energy Demand, Urban Land Occupation, Water Depletion, Terrestrial Acidification, Particulate Matter Formation, Marine Ecotoxicity, and Urban Land Occupation.
   High carbon waste produces higher emissions; open dumping causes waste accumulation because plastic from virgin resin takes a long time to degrade, and plastic waste not collected at the source tends to be burned carelessly and drifts into the sea (Neo et al., 2021). The distance of the landfills, which is too far, increases the burden of transportation emissions and the physical impact of garbage truck operations on the road surface (Neo et al., 2021; Tiogana, 2020). The behavior of end users of plastic products tends to dispose of plastic waste carelessly (Yola, 2013), thus complicating the collection process. Uncollected plastic waste tends to be washed into water bodies and/or burned illegally (Neo et al., 2021).

3.4. Solution Engineering

According to (Kara et al., 2023), engineering solutions are the operational answer to the emission reduction target set at the beginning. To reduce the amount of emissions caused, the cause of the hotspot needs to be fixed with an environmental performance improvement strategy (Wenzel et al., 1994) and focus on the LCE approach (Lundquist, 2002). In this research, the emission reduction target is not set absolutely (quantitatively), but a relative reduction with the most optimal target possible.

Engineering solutions are determined normatively from the four causes of hotspots (in hotspot analysis) by changing raw materials, electricity use, fuel use, and improving plastic waste management. Changing raw materials involves changing the composition of plastic types and substituting them with materials other than plastic according to desired performance and usage. Efficient electricity use is achieved through energy efficiency in preparing raw materials and production processes and by replacing energy generation with renewable energy. Efficient use of fuel oil is carried out by optimizing transportation, maintaining engine performance, regulating operations, and/or substituting petroleum fuel with vegetable oil fuel. Improvements in plastic waste management are carried out by improving plastic waste disposal procedures, increasing plastic waste collection, preventing open burning, increasing waste recycling, and controlling plastic waste destruction.

3.5. Mitigation potential

Mitigation potential is an opportunity to reduce emissions that most dominantly cause environmental impacts throughout the life cycle. This step is the identification of life cycle improvement objects that can be a guide in the eco-design of plastic product manufacturing to be developed. In this article, the author identifies mitigation potential starting from the engineering solution component and the demand control component, from both components, then breaks down in more detail into life cycle emission mitigation in figure 6.

Fig. 6. Potential mitigation formulation matrix

Engineering Solution	Foreground / Background	hotspot position: collection	shredding	raw material	transport	pelletizing	transport	production	packaging	distrobution	EOL treatment	Avoid productiom	Demand
raw material change	FG			PFG1									
	BG			PBG1									
electricity use efficiency	FG					EFG1		EFG2	EFG2				
	BG					EBG1		EBG1	EBG1				D1
fuel oil use efficiency	FG		FFB2		FFG1	FFG2	FFG1			FFG1			
	BG		FGB1		FGB1	FGB1	FGB1			FGB1			
improvement of plastic waste handling	FG	WFG1									WFG2	WFG3	
	BG	WBG1									WBG2	WFG 3	

Description:
FG: Foreground
BG: Background
This study divides the potential for mitigating the life cycle of plastic products from hotspot positions into two domains: the foreground system group and the background system group.
Foreground system group:
1. PFG1 : Substitution and Changes in Plastic Types
2. EFG1 : Efficiency of electricity use in pelletizing
3. EFG2 : Efficiency of electricity use in the plastic product production process
4. FFG1 : Efficient use of fuel in transportation and distribution
5. FFG2 : Efficiency of fuel usage in shedding and pelletizing machines
6. WFG1 : Waste management in collection
7. WFG2 : Waste management in EOL treatment
8. WFG3 : Waste Management in Avoided Production

Background system group:
1. PBG1 : Reduce virgin resin and/or replace it with non-plastic materials
9. EBG1 : Replace electricity with electricity from renewable sources
2. FBG1 : Replacing fuel with biofuel
3. WBG1 : Building facilities and infrastructure
4. WBG2 : Prevent plastic exposure to the sea and open burning
5. WBG3 : Conversion of plastic waste into energy

In addition, mitigation potential can also be carried out by controlling the demand for plastic products:
1. D1 : Controlling demand for plastic products

3.5.1. Mitigation potential from raw material change

Plastic raw materials have different thermoforming process responses for each type regarding energy requirements and the impact of direct emissions. The potential for mitigating raw material changes is a response to hotspots in raw material preparation and plastic product production components. The potential for mitigating raw material changes in the foreground domain includes PFG1 and PBG1.
PFG1 is Emission reductions are related to substituting raw materials in the foreground domain, namely using plastic materials with an increase in the content of recycled materials (Mutiara, 2018). Conventional plastic materials are substituted with biodegradable polymers from renewable

raw materials (Chen et al., 2019). In the case of shopping bag products, the most environmentally friendly raw material choice is plastic bags made from recycled plastic (Abidin et al., 2023).

Reducing emissions from changes in the composition of raw plastic types includes replacing PP plastic types (Laurence & Kasena, 2018), PET (Yani & Warsiki, 2013), and other materials (Sutanto & Rumende, 2022) with other types of plastic or recycled plastic (Mutiara, 2018), Polylactic Acid (PLA) (Ningrum & Afiuddin, 2018), and or plastic type with a lower response to electricity (A. Saputra et al., 2023). The replacement of PS plastic type waFs replaced with PVC (Khairona, 2019) and/or PLA (Yola, 2013). The use of reclaimed PET resin from biomass-derived monomers as a substitute for PET (Nicholson et al., 2021). Polyethylene terephthalate is produced from biological materials using 100% sugarcane-based ethanol. (Semba et al., 2018).

PBG1 is related to emission reductions in the background domain, namely by reducing the virgin resin component in raw materials (Mutiara, 2018) and replacing plastic materials with paper (Yola, 2013). In addition, the development of oxo-biodegradable PVC could be an alternative raw material to enhance the sustainability of PVC products (Soekotjo et al., 2024).

3.5.2. Mitigation potential from efficient electricity use

Electricity is a vital input component of plastic production because almost all production processes require electrical energy. Because electricity is mainly generated with fossil fuels or nonrenewable energy, it contributes significantly to GHG emissions, a hotspot lever in the life cycle of plastic products in Indonesia. The mitigation potential of electricity use efficiency is related to hotspots arising from plastic pelletizing, plastic product production, and packaging. The mitigation potential of electricity use efficiency in the foreground domain includes EFG1 and EFG2.

EFG1 is reducing emissions related to the use of pellet production equipment (pelletizing), such as extruders, by making production processes more efficient (Sirait, 2017) and efficiency in engine performance through modifications and maintenance (Ilhamdika, 2017). EFG2 is reducing emissions from electricity use in plastic production through efficiency (Yola, 2013). Operation settings, modification, centralization, or replacement with new machines. Machine operation settings are carried out with an automation system (Evangelista, 2019). Modifications are made in various ways according to the case, for example, replacing the engine with a lower or larger energy engine (Laurence & Kasena, 2018; Noya, 2018; Sutanto & Rumende, 2022) by reducing the length of the conveyor belt on the packaging unit (Evangelista, 2019), with the rearrangement of (work in process) WIP blank middle roll and printed middle roll products (Mutiara, 2018), and replacing the spindle and tube on the ring spinning machine with lighter materials (Utami et al., 2015). Centralization is carried out, for example, by installing a centralized chiller installation (Ibnu, 2019). The efficiency of the production process can also be achieved by replacing the machine with a new one (A. Saputra et al., 2023).

Potential mitigation of electricity use efficiency in the background domain includes EBG1. EBG1 has replaced electricity with electricity from renewable sources in Indonesia, which has various types of renewable energy, such as solar, hydropower, geothermal, wind, and biomass (Subagyo et al., 2021; Wahono et al., 2021). Economically, the selling price of new renewable energy electricity is cheaper than conventional energy (from fossils). If renewable energy becomes a source of electrical energy, Indonesia's emission reduction target can be achieved (Erdiwansyah et al., 2021). The target mix of new and renewable energy in Indonesia for electricity generation by the end of 2025 is 23% (accumulation of 10.6 GW until 2025 and 18.8 GW in 2029), while the average projected growth in electricity demand is 4.9% (State Electricity Company, 2021). Suppose some of the electricity generated from new renewable energy can be allocated to the manufacturing industry, including the plastic industry. In that case, emissions from the plastic product industry can be reduced.

3.5.3. Mitigation potential from efficient use of fuel oil

Diesel fuel is also used for vehicles transporting raw materials and distributing plastic products, as well as diesel fuel for electric generators to drive shredding machines and other production equipment in the plastic industry. The use of fuel oil hotspots affects GHG emissions. Fuel efficiency mitigation options respond to hotspots in the shredding, transport, pelletizing, and distribution components. The mitigation potential of fuel efficiency in the foreground domain includes FFG1, FFG2, and FBG1.

FFG1 is optimizing transportation, and maintaining vehicle engine performance can potentially mitigate fuel efficiency in transportation and distribution. Emission reduction by optimizing transportation includes setting distance, size, and mode of transportation (Sutanto & Rumende, 2022), including the use of sea transportation (Ilhamdika, 2017). Maintaining vehicle engine performance is done through regular engine maintenance (Ilhamdika, 2017). FFG2 is the potential for efficient use of fuel in shredding and pelletizing machines, which includes adjusting the size of the generator engine, such as using an engine that has less power and/or a larger capacity (Noya, 2018), operation according to needs, and maintaining machine performance through maintenance (Ilhamdika, 2017).

Potential mitigation of fuel efficiency in the background domain includes FBG1. FBG1's supportive climate and the availability of land and technology encourage the implementation of biofuels in Indonesia. Biofuels have a positive impact as an alternative fuel for domestic transportation, generate income by exporting excess production, create jobs in several sectors, and reduce carbon emissions sustainably (Jupesta, 2010).

Maximum torque, load, and vehicle mileage can also affect fuel consumption. The use of 30% biodiesel blend fuel (B30) on vehicles > 3.5 tons in fuel consumption at a specific mileage does not result in a significant increase in average fuel consumption (Karuana et al., 2020). Substituting diesel oil with biodiesel can reduce the impact of emissions on the plastic product industry. Efforts that can be made to reduce the environmental footprint in the PET recycling system include using more environmentally friendly energy and fuels. This can also overcome the problem of poor chemical and water waste management (Rahman & Gandasasmita, 2024).

3.5.4. Mitigation potential from improving plastic waste management

Handling plastic waste is an important issue in reducing the environmental impacts of plastic products. Unmanaged plastic waste causes air, land, and ocean pollution, impacting human health, global warming, and the ecosystem. The potential mitigation of improving plastic waste management related to hotspots in the collection process component, EOL treatment, and avoiding production in the foreground domain is described as follows.

Waste management in collection (WFG1) is increasing plastic waste collection through increasing collection activities (Tiogana, 2020). Collection and recycling of waste through the role of the Waste Bank (Firdaus Pambudi et al., 2016).

Plastic waste management can be done by implementing waste banks, which act as agents in collecting and sorting waste (Irwanto & Wibowo, 2023; Rahayuningtyas et al., 2023). Developing a Waste Bank requires cooperation from various parties, including the Regional Government, local communities, and academics (Nashir et al., 2020).

Waste management in EOL treatment (WFG2), such as improvement of disposal procedures through the cultivation of plastic waste disposal procedures and increasing awareness of plastic waste disposal methods (Neo et al., 2021). Recycling plastic waste (Sutanto & Rumende, 2022; Neo et al., 2021; Ningrum & Afiuddin, 2018; Ibnu, 2019; Firdaus Pambudi et al., 2016), recycling PET plastic waste into plastic pellets (Amirudin et al., 2022), implementation of circular economy and strengthening of 3R (reduce, reuse, recycle) activities (Noya, 2018) recycling of plastic waste through the application of circular economy and the use of Adaptive manufacturing methods (Kuclourya et al., 2022). Plastic waste can be changed into CFRP (carbon fiber reinforced polymer) polymer stone material (Pimenta & Pinho, 2011). Building awareness of sustainable consumption through regular training and monitoring for local communities (Widyaningsih, 2019). Implementing the Waste Bank can also increase the recycling of plastic waste into craft items (Ulfah et al., 2023), thus increasing the community's economic activities. (Ghaffar et al., 2021). The LCA analysis of sustainable energy development from the conversion of plastic waste shows that only filtering has no impact on the environment. This conversion process will benefit the waste bank Banjarnegara, the community, and the government (Martini et al., 2024).

Waste Management at Avoid Production (WFG3) such as The final destruction of plastic waste is controlled through the principle of open-loop recycling (Noya, 2018; Yola, 2013) burning in a special incinerator (Noya, 2018; Neo et al., 2021; Firdaus Pambudi et al., 2016). Producers must plan, implement, monitor, evaluate, and report to reduce waste produced by producers.

The mitigation potential of improving plastic waste handling in the background domain is as follows: WBG1 and WBG2. Building facilities and infrastructure (WBG1) to collect plastic waste is necessary to increase the amount and percentage of collection *(Neo et al., 2021; Noya, 2018; Yola, 2013)*. Prevent plastic exposure to the sea and open burning (WBG2). One of the continuations of the problem of not collecting plastic waste or disposing of plastic waste in the wrong place is the exposure of plastic waste to the sea or being burned carelessly by the community to be destroyed by the environment. For that, it is necessary to prevent the exposure of plastic waste to the sea *(Neo et al., 2021)*, and prevent open burning by increasing the collection ratio *(Neo et al., 2021; Noya, 2018)* and encourage active participation in preserving the environment *(Fitri S et al., 2024)*. To reduce exposure to plastic waste in the sea, multilayer plastic waste is made into paving blocks, which have a better environmental impact than being used as landfill *(Sinaga et al., 2023)*.

Converting plastic waste into energy (WBG3) is the last way to return it to its original raw material function: energy. Some examples of converting plastic waste into energy are energy conversion in the cement industry, Refuse Derived Fuel (Neo et al., 2021), and converting plastic waste into fuel oil through the pyrolysis process on an adequate (economic) scale (Fivga & Dimitriou, 2018; Martini et al., 2024).

3.5.5. Mitigation potential of controlling demand for Indonesian plastic products

Controlling demand for plastic products (D1) is an effort to control the use of plastic products in Indonesia. It has been widely implemented through implementing regulation to reduce and prohibit the use of plastic in everyday life. Because the mitigation option to reduce the demand for plastic products has become the object of government policy, the author does not further explore the mitigation options from the demand component. It is assumed that the demand for plastic products in Indonesia by the 2025-2035 projection will be 44-10 kg/per capita per year. For example, two groups of plastic waste should be restricted from single-use plastic products and fishing equipment. (Directive (EU) 2019/904) European Union (Kasznik, 2023).

3.6. Sensitivity Analysis

This article was compiled through a literature review, emphasizing the importance of reference validity. Sensitivity analysis is necessary to ensure the reliability of the references used. This research focuses on three sub-themes: (1) the Life Cycle Assessment (LCA) of Indonesian plastic products, (2) Life Cycle Engineering (LCE), and (3) plastic product innovation for improving its life cycle. The first sub-theme, *Indonesian Plastic Products*, has been elaborated in Subsection 2.1.

The second sub-theme was developed through a search on Scopus using the keyword *"life cycle engineering"*, with filters set to *"final document," "English,"* and *"keyword Life Cycle Engineering,"* yielding 348 documents (accessed on April 14, 2023). A bibliometric analysis using *VOSviewer* identified nine author clusters. Further investigation of Cluster 7, which includes Kara, Hauschild, and Jeswiet, led to references such as (kellens, 2018; Jamwal et al., 2021; Lundquist, 2002; Wenzel et al., 1994;

Fivga & Dimitriou, 2018). The concept of LCE has evolved since 1998, gained popularity in 2014, and has primarily focused on its implementation as a problem-solving tool. A related conference on this topic is *Procedia CIRP*.

The third sub-theme was developed through searches on Scopus and Google Scholar to identify articles related to mitigation strategies and solutions for improving the life cycle of Indonesian plastic products. The references obtained include (Setiastuti et al., 2023; Subagyo et al., 2021; Wahono et al., 2021; Jupesta, 2010; Firdaus Pambudi et al., 2016; Irwanto & Wibowo, 2023; Rahayuningtyas et al., 2023; Nashir et al., 2020; Kuclourya et al., 2022; Pimenta & Pinho, 2011; Ulfah et al., 2023; Ghaffar et al., 2021; Fitri S et al., 2024; Fivga & Dimitriou, 2018; Martini et al., 2024; Kasznik, 2023). Through the three methods above, adequate references will hopefully be obtained to gather the scientific information needed in this research.

4. Conclusion

The results of LCA hotspot mapping of Indonesian plastic products show that major and minor hotspots are in the cycle components: collection, shredding, raw materials, transportation, pelletizing, production, packaging, distribution, EOL treatment, and avoidance production. The most considerable emission impacts that are hotspots in the analyzed life cycle include 27 midpoint impact categories in 3 endpoint areas, namely human health, ecosystem quality, and resources. The hotspot analysis results revealed that the causes of hotspots consisted of machines, generators, vehicles, materials, open burning, drift to sea, open dumping, and unmanaged plastic waste. These were grouped into four main causes: use of plastic, use of electricity, use of fuel, and Unmanaged waste.

Engineering solutions are carried out normatively by changing raw materials, increasing electricity and fuel use efficiency, and improving plastic waste management. Changes in raw materials are made by replacing the type of plastic or substituting it with other more environmentally friendly materials. Efficient use of electricity and fuel is achieved through energy efficiency in production, replacing it with environmentally friendly electricity sources, optimizing transportation, maintaining machine performance, regulating operations, and using environmentally friendly fuels. Improvements in plastic waste management are made by improving plastic waste disposal, preventing open burning, increasing waste recycling, and controlling plastic waste disposal.

The potential mitigation of improving the life cycle of plastic products is grouped into two domains, namely, the foreground and the background system. The potential mitigation in the foreground system group includes substitution of plastic types, changes in the composition of plastic types, efficient use of electricity in pelletizing, efficient use of fuel in transportation and distribution, efficient use of fuel in shredding and pelletizing machines, waste management in collection, waste management in EOL treatment, waste management in avoid production. The potential mitigation in the background system group includes reducing virgin resin and/or replacing it with non-plastic materials, replacing electricity with electricity from renewable energy sources, replacing fuel with biofuel, building waste facilities, and infrastructure, preventing exposure of plastic to the sea and open burning, and converting plastic waste into energy. In addition, potential mitigation can also be achieved by controlling the demand for plastic products. Improving the life cycle of Indonesian plastic products requires the involvement of external parties, including the National Electricity Company (PLN), the environmentally friendly resin industry, the recycling industry, the waste management industry, and various institutions. It also requires the participation of plastic user communities and law enforcement for violations of plastic use regulations.

The study emphasizes a practical approach to LCE, focusing on translating hotspot analysis into actionable steps. These steps involve considering the entire product life cycle from raw material extraction to disposal ("cradle to grave") and distinguishing between factors that can be directly influenced by manufacturers (foreground systems) and those that are part of the broader infrastructure and energy systems (background systems). By identifying the root causes of environmental impacts and proposing targeted engineering solutions, this research aims to provide a framework for Indonesian plastic product manufacturers to reduce their environmental footprint and contribute to achieving sustainable development goals. This includes strategies related to material selection, energy efficiency, waste management, and product design, encouraging a shift toward a circular economy model for plastics. The limitation of this study is that the analysis focuses solely on plastic products evaluated using the LCA approach. The analysis does not take into account economic and social factors.

Based on the analysis of plastic product life cycle hotspots in Indonesia, the managerial implications that can be taken are the need to focus on reducing plastic use, increasing energy efficiency, and better waste management. Companies need to consider the type of plastic used, considering that some types, such as PET, PS, and PP, significantly impact GHG emissions. Investment in more environmentally friendly thermoforming technology and more energy-efficient production machines can reduce the overall environmental impact. In addition, the energy sources used also need to be considered, such as switching to renewable energy sources to reduce emissions from electricity use.

Furthermore, companies need to implement effective waste management practices to minimize the negative impacts of plastic waste. This can be done by increasing recycling, developing easily recycled products, and implementing an integrated waste management system. Given the importance of these factors, companies should also conduct periodic life cycle evaluations to identify hotspots and measure the effectiveness of mitigation efforts that have been made. By integrating Life Cycle Engineering principles into the design and production process, companies can develop more sustainable plastic products and reduce the environmental impact of the plastic industry in Indonesia.

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