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Life Cycle Assessment of Recycling Polyethylene Terephthalate (PET): A Comparative Case Study in Taiwan

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Abstract: Polyethylene terephthalate (PET) is commonly used in beverage container manufacturing; however, its classification as a single-use plastic significantly contributes to environmental pollution. Improper disposal results in enduring contamination of both terrestrial and marine ecosystems, which poses ecological and health risks. Among the disposal methods, recycling, incineration, and landfilling, only recycling promotes a circular economy by reducing reliance on landfills, alleviating emissions, and conserving fossil resources. This study employs the life cycle assessment (LCA) method to evaluate the environmental impacts of three PET bottle recycling facilities in Taiwan, considering collection, transportation, and processing in the system boundary. It also assesses the effects of raw material composition, comparing transparent, colored, and mixed PET bottles. The results indicate that facilities processing colorless PET have lower environmental damage values (16.6–18.1 mPt·kg^{-1} of recycled flakes) than those handling colored and oil-trapped PET (25 mPt·kg^{-1}) due to higher energy demands and poly aluminum chloride usage in wastewater treatment. Granulation was identified as a significant environmental hotspot for recycled PET pellets, with a damage value of 35 mPt·kg^{-1}. Integrating renewable energy and recycled PET into PET bottle manufacturing could significantly reduce their environmental impacts. Policy recommendations include adopting renewable energies as the source energy, calibrating the use of chemicals in recycling facilities, and mandating minimum recycled content in PET products to enhance circularity.

Keywords: PET bottle recycling; life cycle assessment; environmental impact assessment; circular economy

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1. Introduction

Plastics play a critical role in modern industry and daily life, with global production reaching approximately 370 million tons in 2019 [1]. However, the accumulation of plastic waste has become a significant environmental challenge, necessitating sustainable waste management strategies to mitigate fossil resource depletion. In the last fifty years, the production of plastics has steadily increased, and based on the Organization for Economic Co-operation and Development (OECD), the production could triple in the next 40 years [2]. In order to realize the Sustainable Development Goals (SDGs), it is essential that all sectors align their strategies with the objectives outlined by the SDGs. Consequently, sustainable management strategies are necessary across all domains, including research, industry, and government. This alignment is important for mitigating the effects of plastic pollution on

ecosystem services and human health. The circular economy, which promotes reusing, recycling, and transforming waste into raw materials, has become necessary for achieving a sustainable world. Recycling is increasingly recognized as the most effective approach to reintegrating plastic waste into material life cycles while minimizing its ecological impact [3]. Polyethylene terephthalate (PET), which constitutes approximately 7% of the global plastic demand [4], is predominantly used in beverage containers, accounting for 62% of the total plastic bottle production worldwide [5]. PET plastic bottles are made of solid materials that do not absorb water, making them suitable for food and beverage packaging. In Taiwan, PET plastic containers constitute the largest share of collected plastic waste, with an annual recycling volume of approximately 100,000 tons [6]. Implementing mandatory waste-sorting policies since 2005 has significantly enhanced recycling efficiency, resulting in a national recycling rate of 55.14% and a PET container recycling rate exceeding 95% [7]. Taiwan's PET recycling industry primarily utilizes physical processing techniques, including washing, label removal, and shredding [8]. PET production relies on fossil fuel extraction and significant energy inputs, while disposal through incineration or landfilling limits its reusable potential. Transitioning from a linear to a circular economy is essential to enhance material reuse, recycling, and refurbishment. This shift reduces raw material consumption, lowers environmental emissions, and mitigates ecological burdens [9]. The 2018 "New Plastic Economy Global Commitment" by the Ellen MacArthur Foundation promotes plastic circularity through redesign, reuse, and recyclability. It seeks to eliminate problematic plastics, reduce single-use packaging, and ensure all packaging is recyclable or compostable. The initiative also aims to decouple plastic production from resource consumption while eliminating hazardous substances. Over 500 entities have pledged to meet these goals, with businesses required to ensure 100% recyclable, reusable, or compostable packaging by 2025 [10]. In 2019, the European Union (EU) consumed 50 million tons of plastic, contributing to the 80–85% share of plastic waste in marine debris [11]. To address this growing issue, the European Plastics Strategy (EPS) aims to ensure that all plastic packaging is reusable or recyclable by 2030 [12]. Directive (EU) 2019/904 targets single-use plastics and PET bottles under 3 liters, requiring at least 25% recycled content by 2025 and 30% by 2030 [13]. EU Member States must achieve a 77% collection rate for these bottles by 2025, reaching 90% by 2029. Since October 2020, the United Kingdom (UK) has banned certain single-use plastics and aims to eliminate all single-use plastic waste by 2042. However, limited recycling capacity results in the export of 60% of plastic waste [14]. The recycling rate of plastic beverage bottles is 77%, whereas the overall plastic waste recycling rate remains at 59% [15]. The UK aims to address this issue by implementing a Deposit Return Scheme (DRS), with Scotland initiating the program in 2022, and a nationwide rollout planned for 2023. In the United States (U.S.), the PET recycling rate declined slightly from 29.2% in 2017 to 28.9% in 2018, remaining relatively stable over the past decade [16]. To compensate for the decline in exports due to China's waste import ban, recyclers increased PET bottle procurement by 16%. In response, the American Chemistry Council (ACC) introduced a plastic circularity strategy, Operation Clean Sweep (OCS), that seeks to mitigate plastic pollution. Taiwan's high recycling rate is driven by its 1997 "Four-in-One Recycling Program" and the 2005 "Mandatory Waste Classification and Zero Waste Policy", which ensure proper waste separation, leading to a recycling rate of 51% [17]. PET bottle recycling methods include physical and chemical recycling, but Taiwan primarily relies on mechanical recycling due to high costs and regulatory restrictions. Mechanical recycling involves collecting, sorting, cleaning, and shredding PET bottles into flakes, which are then converted into fibers or processed into granulates for manufacturing new plastic products. Mechanical PET recycling offers several advantages, including a straightforward processing method with low capital investment [18], and accommodating a diverse

range of raw materials, such as transparent, colored, and oil-contaminated PET bottles [19]. Furthermore, compared to chemical recycling, the mechanical process generates lower environmental emissions, thereby reducing PET waste's ecological impact [20]. However, notable limitations exist; the quality of recycled PET deteriorates with each processing cycle, leading to a decline in color and mechanical properties [21]. Additionally, cross-linking and oxidation reactions contribute to the yellowing of the material [22]. Furthermore, thermal and hydrolytic degradation alter PET's molecular weight and viscosity characteristics, presenting a critical challenge in mechanical recycling [23]. Chemical recycling of PET depolymerizes polymers into monomers or oligomers, enabling virgin-quality PET production but requiring large-scale operations for economic viability. Key methods for this include methanolysis, glycolysis, hydrolysis, and aminolysis. Glycolysis, the most commercially viable, uses Ethylene Glycol (EG) to break ester bonds, producing bis-hydroxyethyl terephthalate (BHET) for PET manufacturing [24]. Methanolysis and hydrolysis yield high-quality products but are costly and time-consuming [21–24], while aminolysis remains limited to specific fiber applications [25]. Despite its potential, PET chemical recycling faces challenges in efficiency and scalability, with glycolysis being the most widely adopted industrial method.

Several studies have assessed the environmental impact of recycled plastics using Life Cycle Assessment (LCA) methodologies worldwide. Among these studies, Zhang et al. (2020) [26] analyzed the production of one metric ton of recycled PET blankets in China, identifying organic chemical agents and the fiber-drawing process as major contributors to environmental impact and costs. Their study suggested that adjusting the energy mix to reduce coal-fired electricity could mitigate pollution emissions. Similarly, Wang et al. (2019) [27] examined factory-scale recycled plastic production in China, revealing that indirect production processes had more significant environmental impacts than direct ones, with electricity use, air pollution, and chemical agents as key environmental hotspots. For detailed analysis, Chen et al. (2020) [28] highlighted that electricity consumption in transportation and extrusion processes machinery significantly contributed to various environmental impact categories in mixed plastic waste recycling. In Jordan, Bataineh (2020) [29] assessed the global warming potential (GWP) of one metric ton of recycled PET and high-density polyethylene (HDPE), highlighting that emissions primarily stemmed from the energy consumed during the processing and transportation segment. Their study demonstrated that recycled PET consumed 14% less energy than virgin PET. In Malaysia, Rahim et al. (2017) [30] found that carbon footprints in recycled Polypropylene (PP) and Oriented Polypropylene (OPP) production were mainly associated with electricity consumption and waste management, reporting that producing one kilogram of plastic pellets results in 0.84 kg of CO_2 emissions. Among these, electricity consumption accounts for 73.8%, solid waste generation for 23.3%, and fuel consumption for 2.3%. Martin et al. (2021) [31] investigated recycled PET production in Brazil, identifying chemical additives used in bottle washing as significant contributors to ozone depletion, terrestrial acidification, and freshwater eutrophication. Lastly, Khoo (2019) [32] analyzed Singapore's 2016 plastic waste recycling, reporting that extruder electricity consumption contributed to 62% of total plant energy use. This aligns with the present study's findings, where pelletizing accounted for approximately 50% of the total electricity consumption. Shen et al. (2010) [33] identified wastewater treatment processes as significant contributors to environmental degradation, particularly in terms of eutrophication, human toxicity, and freshwater ecotoxicity. These impacts are largely attributed to the release of residual nutrients and chemicals during treatment, and the energy-intensive nature of the processes involved. Huang (2013) [34] analyzed the carbon and water footprints of three PET recycling plants in the northern, central, and southern regions by incorporating

emissions from waste collection, transportation, and processing, revealing that carbon emissions were highest in the northern plant (304.89 $kgCO_2eq/ton$), followed by the central (251.47 $kgCO_2eq/ton$) and southern (243.83 $kgCO_2eq/ton$) plants. The recycling process accounted for the majority of emissions (85%), primarily due to electricity consumption, heavy oil usage, and surfactants, while transportation from sanitation teams to recyclers contributed over 50% of emissions. Similarly, Zhang (2015) [35] investigated the carbon footprint of recycled polypropylene (PP) pellets and found that producing one kilogram of recycled PP pellets emitted 0.407 $kgCO_2eq$ per FU, mainly from electricity and water consumption. Compared to virgin PP production (1.7 $kgCO_2eq/kg$), recycled PP significantly reduced emissions. Carbon reduction strategies were proposed, potentially lowering emissions by 2.8% per functional unit. Prior studies, including [29–33] Bataineh, 2020, and Shen et al., 2010, have consistently demonstrated that using recycled plastics in PET bottle manufacturing significantly reduces reliance on virgin plastics and lowers CO_2 emissions by approximately 75%. Keul et al. (2024) [36] realized that recycling PET can lead to an 88% reduction in climate change impacts compared to landfill or incineration options. If one can achieve 100% recyclability in PET bottle management, the greenhouse gas emissions from disposal processes can reach up to 90% [37]. These studies highlight the critical role of energy use, chemical additives, and transportation in determining the environmental impact of recycled plastics. Existing studies on PET recycling in Taiwan primarily focus on carbon footprint assessments while lacking comprehensive and simple evaluations of broader environmental impacts to allow non-professionals to understand the real impact on human health and the environment. To address this research gap, this study conducts a life cycle assessment (LCA) of PET recycling at three certified facilities in Taiwan, converting the endpoint results into a single unit that allows decision-makers to understand the impact of this waste category. Utilizing inventory data specific to each facility, it pinpoints significant environmental hotspots by translating impact measurements into milli-points (mPt). This approach yields results in mPt, enabling stakeholders to make informed decisions with a simplified, single-score impact assessment. The mPt is a normalized and weighted unit in life cycle impact assessment (LCIA) that is used to express the aggregated environmental burden of a product or system as a single, comparable score. This is derived from the point (Pt) system, where 1 Pt represents the average annual per capita environmental load in a reference region, usually Europe, and where 1 mPt equals one-thousandth of this benchmark, allowing for easy comparison. The calculation follows a structured methodology involving characterizing life cycle inventory data into impact categories, normalization against regional or global reference values to contextualize significance, and applying weighting factors to reflect the relative importance of each impact. This study proposes optimization strategies to enhance the sustainability of Taiwan's recycled PET plastics market and foster a more robust circular economy, aiming to achieve a sustainable world. Utilizing the LCA methodology, this study adopts a cradle-to-grave approach to assess post-consumer PET containers, encompassing their collection, transportation, and manufacturing at recycling facilities. Environmental impacts are evaluated using SimaPro software 9.0.0.33, particularly the effects of different compositions of transparent, colored, and oil-contaminated PET bottles.

2. Results and Discussions

This research comprehensively assesses and compares the environmental effects of recycling one kilogram of colorless, colored, and oil-contaminated PET. It highlights the opportunity to use recycled PET pellets to produce new PET bottles from the granulates obtained through recycling. A critical part of this analysis is to examine the environmental impacts caused by the variations in processing and production methods of transparent

versus colored and oil, and other chemical-contaminated PET bottles at the three recycling facilities. The environmental impact assessment was conducted using SimaPro 9.0.0.33 software, which applied the ReCiPe methodology for LCIA. The evaluation is standardized per unit of FU, with impact scores derived through characterization, normalization, and weighting factors. The results are expressed in milli-point (mPt). The mPt is an LCIA unit that quantifies the overall environmental damage by aggregating multiple impact categories into a single score. This comprehensive assessment facilitates a rigorous comparative analysis of environmental impacts across the three recycling plants, thereby contributing to a more nuanced understanding of the sustainability and efficiency of PET recycling processes.

2.1. Environmental Impact Assessment Results of Plant A

To ensure consistency and comparability, the environmental impact assessment in this section excludes the pelletization process, as it is only conducted internally by the witness case, Plant A. The LCA endpoint results indicate that the manufacturing stage is the most environmentally impactful across all damage categories. Regarding human health, the total impact calculated is 1.30×10^{-6} disability-adjusted life years (DALY), with the manufacturing stage contributing the highest burden (5.44×10^{-7} DALY), followed by pollution control input (3.55×10^{-7} DALY) and waste processing (2.01×10^{-7} DALY), as described in Table 1. For ecosystem quality (2.19×10^{-9} species. yr total), manufacturing (1.08×10^{-9} species.yr) remains the most significant contributor, with pollution control input (4.67×10^{-10} species.yr) also playing a significant role. Regarding resource depletion (4.15×10^{-2} USD 2013 total), manufacturing (2.17×10^{-2} USD 2013) and raw material extraction (9.25×10^{-3} USD 2013) account for the highest impacts, while the indirect raw material stage (3.28×10^{-3} USD 2013) shows a lower footprint, emphasizing the benefits of recycling. To make these findings more accessible to those without a professional background in sustainability, particularly concerning sustainability decisions in the political sector, the results are presented in mPt. This method emphasizes societal concerns and prioritizes more significant impacts, including effects on human health. The total environmental burden, evaluated at 18.1 mPt per kilogram of recycled PET flakes, is predominantly driven by human health impacts (16.5 mPt, 90.9%), followed by ecosystem damage (1.2 mPt, 6.7%) and resource depletion (0.4 mPt, 2.4%), as illustrated in Figure 1, which explains the total impact converted in one single unit. In most categories, the manufacturing stage, especially energy consumption, is the most ecologically threatened compared to the other stages. These findings highlight the need for cleaner manufacturing facilities and methods to reduce environmental burdens. The pollution prevention inputs, particularly the PAC, H_2SO_4, and NaOH, used in the cleaning process contribute significantly, accounting for 27.2% of human health impacts and 21.3% of ecosystem damage, indicating the need for improved chemical management and filtration techniques during the cleaning process. Additionally, raw material accounts for 16.1% of resource depletion, emphasizing the importance of enhancing material sourcing and handling efficiency. A detailed analysis described in Table S1 in the Supplementary Materials identifies electricity consumption during manufacturing as the leading contributor to human health damage (26.3%), followed by PAC usage in pollution prevention (19.8%), emissions from mixed waste plastic incineration (13.9%), and steam consumption in manufacturing (13.6%). The manufacturing stage accounts for 42.6% (7.71 mPt) of total environmental damage, followed by pollution prevention input (26.6%), process waste (14.8%), indirect materials (10.4%), and raw materials (5.6%). Plant A uses a steam boiler as the energy source for the initial bottle flake washing. This energy source is more sustainable compared to oil used by other facilities.

Table 1. Environmental impact damage in mPt of each stage in Plant A.

Damage Category	Unit	Raw Material Stage	Indirect Raw material Stage	Pollution Control Input Stage	Manufacturing	Waste Processing Stage	Percentage	Total	
Human Health	mPt	8.41×10^{-1}	1.72	4.48	6.87	2.54	90.9%	16.5	18.1
Ecosystem Quality		9.54×10^{-2}	1.37×10^{-1}	2.61×10^{-1}	6.02×10^{-1}	1.28×10^{-1}	6.7%	1.2	
Resource Depletion		9.91×10^{-2}	3.51×10^{-2}	7.13×10^{-2}	2.32×10^{-1}	6.39×10^{-3}	2.4%	0.4	

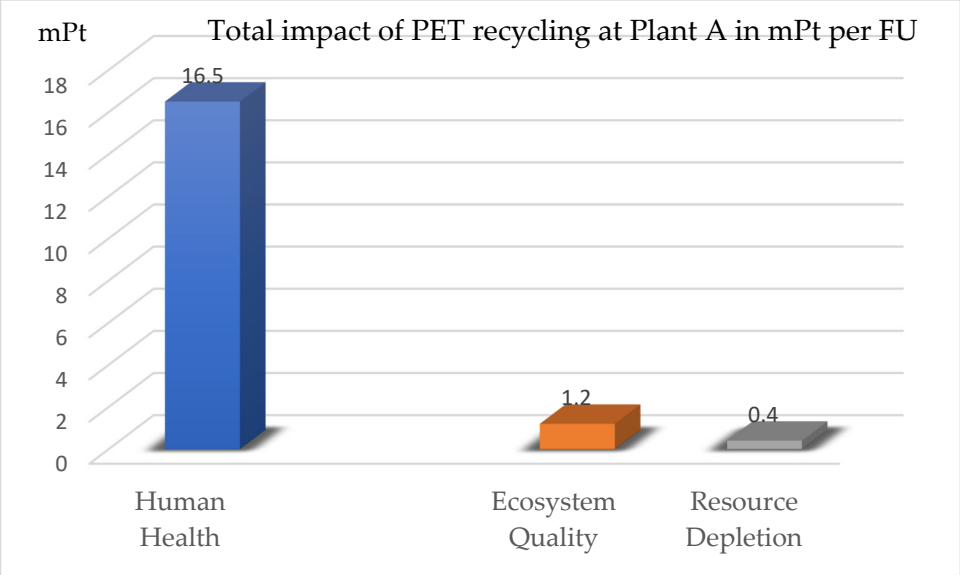


Figure 1. LCA endpoint results of the environmental impact of PET manufacturing on Plant A.

These findings support the need for further improvement in energy efficiency, raw material selection, and waste management to mitigate the environmental burden of PET recycling. One solution could be to focus on integrating renewable energy sources, optimizing chemical usage in pollution control materials, and adopting advanced waste treatment technologies to reduce health and ecological impacts while maintaining the economic viability of recycled PET production.

2.2. Environmental Impact Assessment Results of Plant B

The environmental impact assessment of Processing Plant B per unit FU of recycled material, based on the ReCiPe Endpoint method, yielded the following damage values: 1.19×10^{-6} DALY for human health, 1.92×10^{-9} species·yr for ecosystem damage, and 4.72×10^{-2} USD2013 for resource depletion, as depicted by Figure 2. Table 2 displays the total environmental damage associated with producing one kilogram of recycled PET flakes at Plant B, which is quantified at 16.6 mPt. Among the three damage categories assessed, human health impacts were the most significant, contributing 15.0 mPt (90.4%) of the total, followed by ecosystem damage at 1.1 mPt (6.6%) and resource depletion at 0.5 mPt (3.0%). The dominant contribution to human health impacts was attributed to the manufacturing stage and pollution prevention inputs. A detailed breakdown of damage contributions, presented in Table S2 of the Supplementary Material, identifies the waste processing stage as the major hotspot across all impact categories. Specifically, it accounted for 34.3% of human health damage, 40.4% of ecosystem damage, and 58.3% of

resource depletion. Pollution prevention inputs also had a notable impact, contributing 28.4% to human health damage and 23.1% to ecosystem damage. In comparison, the raw material stage was responsible for 17.4% of the total resource depletion. At the process level, electricity consumption during the processing stage emerged as the largest single contributor to human health damage (27%). Other significant contributors include the use of PAC for pollution control (21%), caustic soda for washing PET flakes (15%), and emissions from the incineration of mixed waste plastics (15%). The remaining processes collectively accounted for 22% of the total environmental damage. These findings support the need to optimize both the waste processing operations and the use of pollution control inputs, including chemicals at Plant B. The observed environmental impacts, particularly from energy use and chemical inputs, illustrate the rebound effects associated with circular economy practices in the plastics recycling sector. Addressing these impacts is essential to ensuring that recycling efforts contribute effectively to a sustainable and low-impact PET manufacturing industry.

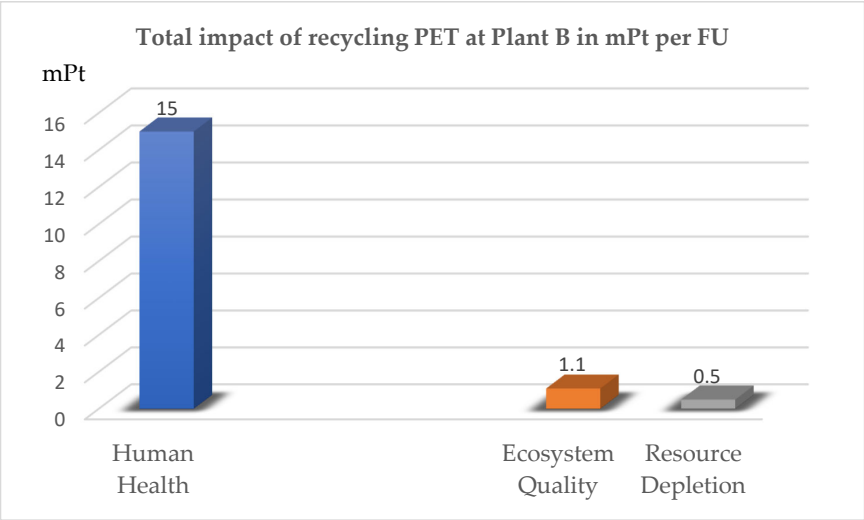


Figure 2. LCA endpoint results of the environmental impact of PET manufacturing on Plant B.

Table 2. Environmental impact damage in mPt of each stage in Plant B.

Damage Category	Unit	Raw Material	Indirect Raw Material	Pollution Control Inputs	Manufacturing	Waste Processing	Percentage	Total	
Human Health	mPt	5.96×10^{-1}	2.43	4.27	5.16	2.58	90.4%	15	16.6
Ecosystem Quality		6.00×10^{-2}	1.93×10^{-1}	2.47×10^{-1}	4.32×10^{-1}	1.36×10^{-1}	6.6%	1.1	
Resource Depletion		8.48×10^{-2}	5.15×10^{-2}	6.42×10^{-2}	2.95×10^{-1}	1.06×10^{-2}	3%	0.5	

2.3. Environmental Impact Assessment Results of Plant C

This section presents the environmental impact assessment results of producing one kilogram of recycled PET flakes at manufacturer C using the ReCiPe Endpoint Method. The pollution control inputs, PAC, etc., are identified at this recycler as the leading environmental burdens. Plant C manufactures colorful PET and other types, including bottles trapped with oil and other chemicals that must be washed before recycling. The LCA endpoint impact assessment results described human health, ecosystems, and resource depletion. The calculated damage values per FU were 1.82×10^{-6} DALY for human health,

2.77×10^{-9} species. yr for ecosystems, and 4.65×10^{-2} USD (2013) for resource depletion (Figure 3). A deeper analysis of the contributions of different processing stages to these environmental damage categories indicates that the pollution control input stage exerts the most significant impact on human health and ecosystems, contributing 45.8% and 37.6%, respectively, as shown in Table 3. However, the manufacturing stage was identified as the primary contributor to resource depletion, accounting for 36.1% of the total impact. The total environmental damage per FU was estimated at 25 mPt when aggregating the weighted damage results across all impact categories. Of the three categories, human health was the most affected, contributing 23 mPt (92%) of the total impact, followed by ecosystems at 1.5 mPt (6.2%) and resource depletion at 0.5 mPt (1.8%) (Figure 3). Given its significant impact on human health, a detailed analysis was conducted to identify key contributing factors. The key contributors identified were PAC in pollution control inputs (40%), electricity consumption during manufacturing (27%), and caustic soda usage in the indirect raw material stage (12%) (see Table S3 in the Supplementary Materials). Environmental damage values across processing stages indicate that the pollution control input stage causes the most significant impact, contributing 11.3 mPt (45.2%). This is followed by the processing stage at 7.4 mPt (29.6%), while the indirect raw material stage, waste processing stage, and raw material stage account for 3.2 mPt (12.8%), 2.2 mPt (8.8%), and 0.9 mPt (3.6%), respectively. These findings highlight the necessity for targeted mitigation strategies to minimize the environmental footprint of PET recycling at these recyclers. Specifically, interventions aimed at reducing PAC and caustic soda use, optimizing energy consumption in manufacturing, and improving waste management practices could significantly lower the adverse environmental impacts of recycled PET flake production.

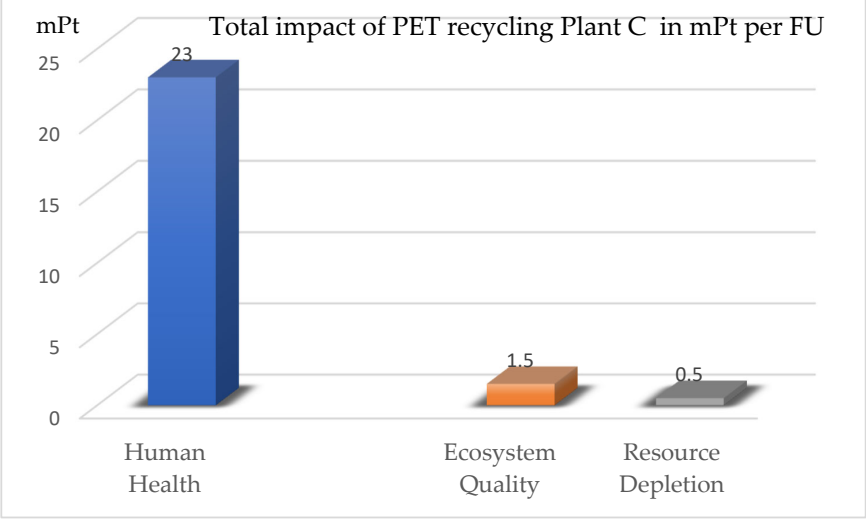


Figure 3. LCA endpoint results of the environmental impact of PET manufacturing on Plant C.

Table 3. Environmental impact damage in mPt of each stage in Plant C.

Damage Category	Unit	Raw Material	Indirect Raw Material	Pollution Control Input	Manufacturing	Waste Processing	Percentage	Total	
Human Health	mPt	9.25×10^{-1}	3.21	1.13×10^{-1}	7.45	2.21	592%	23	25
Ecosystem Quality		7.47×10^{-1}	2.92	1.05×10^{-1}	6.73	2.09	6.2%	1.5	
Resource Depletion		8.26×10^{-2}	2.31 x 10^{-1}	5.81×10^{-1}	5.42×10^{-1}	1.11×10^{-1}	1.8%	0.5	

2.4. Comparison of the Environmental Impact of the Different Processing Plants

PET bottles are much more suitable for consumer behavior in storing liquids, making them essential in human daily life [38], and explaining the increased amount of this waste category in the environment. A comparative environmental impact assessment of three PET recycling Processing Plants is conducted using the ReCiPe Endpoint method, and the results are described in Table 4 and Figure 4. The analysis indicates that human health is the most impacted across all three plants, with total environmental damage values of 18.1 mPt, 16.6 mPt, and 25 mPt for Processing Plants A, B, and C, respectively. Processing Plant C exhibits the highest environmental burden, as depicted by Table 4, primarily due to the type of PET bottle being processed, such as colorful and waste-contaminated PET bottles, which account for 98.9% of its input materials, compared to Processing Plants A and B, which mainly process transparent PET bottles (87.85% and 77.56%, respectively).

Table 4. Endpoint results of each Processing Plant expressed in mPt.

Damage Category	Unit	Plant A	Plant B	Plant C
Human Health	mPt	16.44	15	23
Ecosystem quality		1.22	1.1	1.55
Resource Depletion		0.44	0.5	0.45
Total		18.1	16.60	25

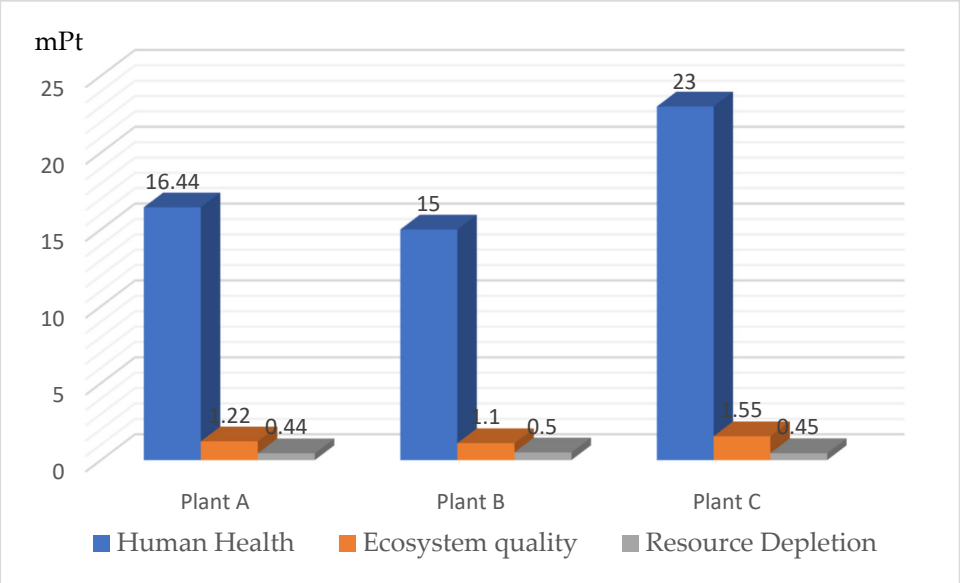


Figure 4. Comparison of environmental damage at each Processing Plant.

Detailed analysis reveals that electricity consumption during manufacturing primarily contributes to environmental damage in Processing Plants A and B, accounting for 27% of their total impact (Table 5). However, PAC usage in the pollution control inputs stage is the most significant contributor to Processing Plant C's impacts, responsible for 39% of its environmental damage. Moreover, mixed waste plastics, including non-recyclable plastic sheets, labels, and composite materials, represent a significant environmental burden across all three plants due to their disposal through incineration. Processing Plant A employs a steam boiler for the initial bottle flake washing, Plant B relies on a fuel oil boiler, and Plant C utilizes a natural gas boiler. Additionally, diesel consumption at all three facilities is primarily used for on-site machinery and transportation, contributing to their

overall energy demand. These variations in energy sources may lead to differences in environmental impact.

Table 5. Environmental hotspots analysis of the three Processing Plants.

Hotspot Ranking	Plant A		Plant B		Plant C	
	Component	**Percentage**	**Component**	**Percentage**	**Component**	**Percentage**
1	Electricity	27%	Electricity	27%	PAC	39%
2	PAC	19%	PAC	20%	Electricity	27.5%
3	Steam	14.2%	Caustic Soda (liquid)	15%	Soda flakes	12.5%
4	Mixed plastics Waste	13.2%	Mixed plastics Waste	14.1%	Mixed plastics Waste	7.3%

Detailed analysis of waste processing (Figure 5) shows that organic sludge generation varies across the plants. Processing Plants A, B, and C produce 0.053 kg, 0.062 kg, and 0.072 kg of sludge per FU of recycled PET flakes, respectively. The higher sludge generation in Processing Plant C is associated with its more significant proportion of colored and oil-trapped PET bottles, which often contain large amounts of residual contaminants from products such as salad oils, soy sauce, etc., that must be cleaned out before processing. These residues require additional wastewater treatment systems employing chemicals, leading to an increase in sludge production. While not a primary objective, this study tracked carbon emissions at each stage of PET waste recycling to inform data-driven policy recommendations. Figure 6 illustrates CO_2 emissions across the recycling facilities. The life cycle carbon emissions analysis shows distinct patterns across the three plants. Plant C has the highest total emissions (0.741 $kgCO_2/kg$), mainly from raw material (23.5%) and the processing stages (44.52%), indicating inefficiencies in sourcing and energy use. Plant A has the lowest total emissions (0.631 $kgCO_2/kg$), due to lower raw material (9.28%) and processing emissions (34.83%), but higher pollution control (32.49%) and waste stage emissions (23.4%). Plant B shows a more balanced profile, with moderate emissions (0.644 $kgCO_2/kg$) across all stages.

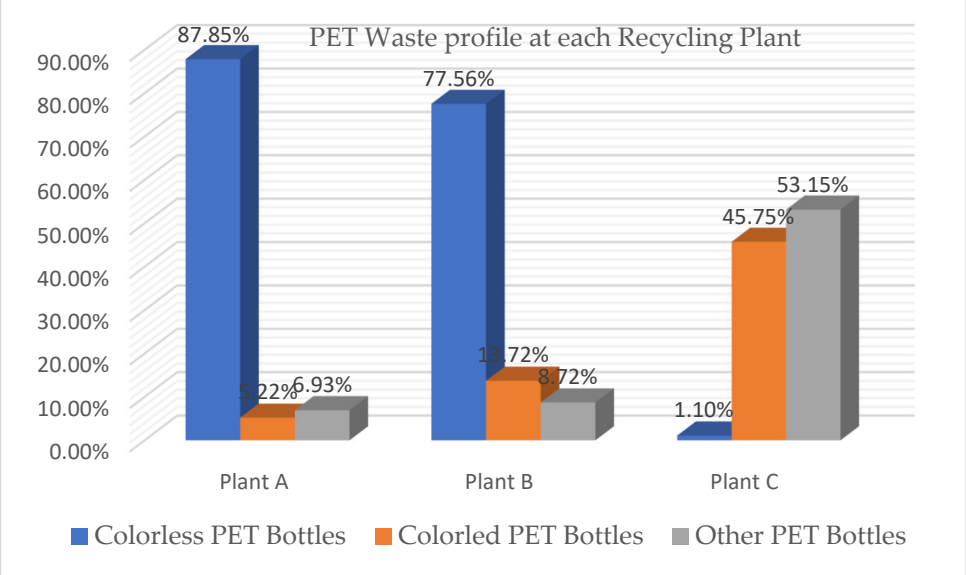


Figure 5. Description of the type of PET bottles treated by each plant.

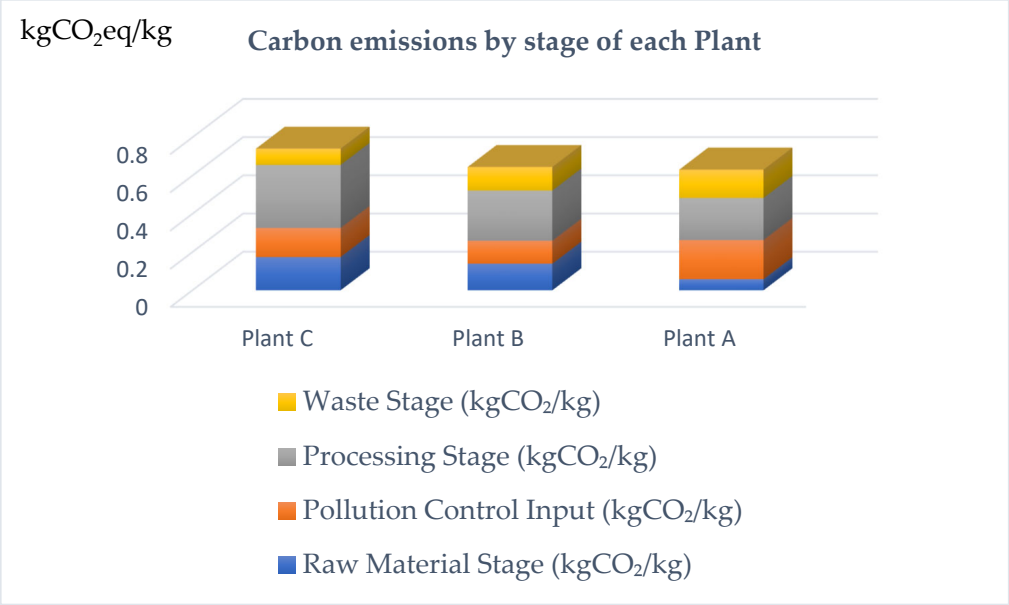


Figure 6. Carbon emissions by stage of the three Plants.

2.5. Environmental Impact Assessment Results of Recycled PET Pellets

The manufacturing of PET and its usage have resulted in unintended consequences for the environment and human health, as shown in the results of this study, due to the large amount of PET bottles being disposed of in the ecosystems [39]. Recycled (PET) is derived from post-consumer PET containers that undergo processing to produce reusable material, typically in the form of flakes or pellets. This study employed a methodological approach to comprehensively assess the overall environmental impact of producing one kilogram of recycled PET pellets within an integrated PET recycling system that aims to produce granulates of PET. The analysis encompassed the process, from collecting discarded PET containers to producing pellets at the processing facility. The detailed results are described in Table 6 and Figure 7, which show the LCA endpoint results. The pelletizing stage completed by Plant A highlights an essential impact of 34.59 mPt (Table 7). Compared to the previous system boundary, this stage is more unsustainable than others are.

Table 6. Detailed LCA endpoint results of PET pellet manufacturing.

Damage Categories	Unit	Bottle Flake Stage	Pelletizing Stage	Total
Human Health	DALY	1.30×10^{-6}	1.20×10^{-6}	2.50×10^{-6}
Ecosystem Service	species.yr	2.19×10^{-9}	2.10×10^{-9}	4.29×10^{-9}
Resources Depletion	USD2013	4.15×10^{-2}	2.71×10^{-2}	6.86×10^{-2}

Table 7. Detailed LCA endpoint results expressed in mPt of granulation.

Damage Categories	Unit	Bottle Flake Stage	Pelletizing Stage	Percentage	Total	
Human Health	mPt	16.4	15.13	91.3%	31.53	34.59
Ecosystem Service		1.2	1.17	6.7%	2.37	
Resources Depletion		0.4	0.291	2%	0.69	

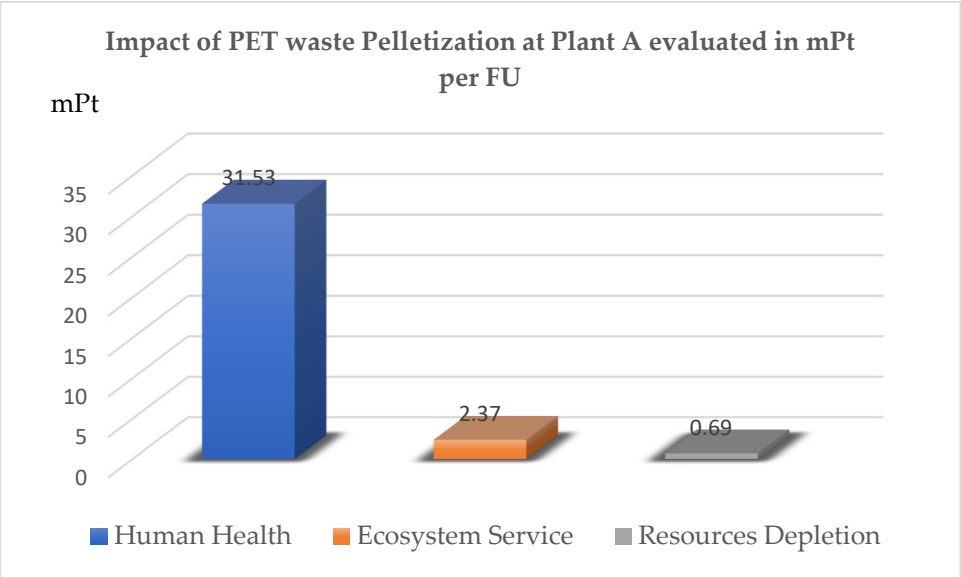


Figure 7. LCA endpoint results of pellet manufacturing at Plant A.

Considered as the witness case, the environmental impact assessment of plastics pelletization at Processing Plant A was conducted using the ReCiPe endpoint method, including human health (2.50×10^{-6} DALY), ecosystem quality (4.29×10^{-2} species.yr), and resource depletion (6.86×10^{-9} USD2013) (Table 7) per FU of recycled (PET) pellets. The contributions from the two primary production stages, flake production and pelletizing, demonstrated minor variations across these categories. Flake production contributed 52% to human health damage, 51% to ecosystem quality, and 61% to resource depletion, whereas the pelletizing stage accounted for 48%, 49%, and 39%, respectively. The total environmental damage value per kilogram of recycled PET pellets was estimated at 34.5 mPt, with human health impacts dominating (91.3%), followed by ecosystem quality (6.7%) and resource depletion (2%). A detailed analysis of environmental impact within the pelletization stage identified electricity consumption as the primary contributor to overall environmental damage, accounting for 97.8% of human health (14.8 mPt), 96.6% of ecosystem quality (1.13 mPt), and 85.9% of resource depletion (0.25 mPt) impacts (see Table S4 in the Supplementary Materials). The extruding equipment used in pelletizing was identified as a key hotspot, reinforcing the need for targeted energy efficiency interventions to improve sustainability in these PET recycling facilities. Global warming potential ($kgCO_2eq$) emerged as the most significant concern, consistent with findings from many previous studies, including Bataineh (2020) [29] on PET recycling in Jordan, Shen et al. (2010) [33] on recycling processes, and Huang (2013) on recycling plants in Taiwan. A key difference noted between the actual study's results and Huang 2013 [34] is primarily due to variations in system boundaries, with the present research incorporating waste treatment processes, leading to higher reported global warming potential values. Additionally, discrepancies in environmental impact assessments across studies were attributed to regional differences in electricity sources, tap water treatment, and raw material selection. However, relying on a single environmental impact category is insufficient for a comprehensive assessment of the overall environmental benefits of recycled plastics. Multicriteria decision-making tools, such as the Analytical Hierarchy Process (AHP), have been utilized to evaluate PET recycling technologies, with findings suggesting that pelletizing is the most effective method, followed by incineration with waste recovery [40]. A holistic assessment incorporating multiple environmental impact categories is necessary to evaluate PET recycling's sustainability benefits. This study's findings highlight PET

recycling's environmental benefits, primarily due to eliminating petroleum extraction and substantially reducing CO_2 emissions. A multifaceted approach is required to improve the environmental sustainability of the PET recycling facilities in Taiwan. These approaches encompass transitioning to renewable energy sources, especially wind power, and investing in energy-efficient equipment, which can substantially reduce emissions associated with electricity consumption, constituting the primary source of greenhouse gas emissions in the recycling process. Transportation-related emissions can be mitigated by optimizing logistics, including establishing decentralized waste collection hubs and adopting low-emission vehicles. Additionally, substituting conventional surfactants with environmentally-benign alternatives and redesigning processes to minimize chemical and water inputs can reduce the environmental burden. Enhancing closed-loop recycling systems, particularly through bottle-to-bottle recycling, and fostering collaborations with manufacturers to promote the design of recyclable products are essential for increasing material recovery and reducing dependency on virgin plastics. Public engagement through education on proper waste separation and policy incentives supporting low-carbon technologies can reinforce these efforts. Moreover, integrating digital technologies such as artificial intelligence and the Internet of Things for real-time monitoring and logistics optimization presents significant opportunities for improving operational efficiency and reducing emissions across the recycling value chain. While reusing PET versus sourcing new raw materials can have ecological benefits, one may need to assess the economic feasibility to understand the overall scope. Future research should focus on developing alternative, less environmentally harmful chemical inputs, and exploring the potential of integrating renewable energy to enhance the sustainability of the PET recycling process.

3. Methods

3.1. Goal and Scope, Functional Unit, and System Boundary of the Study

The primary goal of this LCA is to evaluate the environmental impact of producing recycled PET bottle flakes and pellets from waste PET plastic containers. These containers, categorized as transparent bottles, colored bottles, and oil-trapped bottles, are remanufactured in three selected recycling plants (A, B, and C) in Taiwan. The environmental impact of these three types of PET bottles is compared to understand how the differences in color and raw materials sourcing, including oil and other trapped chemicals bottles, affect the sustainability index of these manufacturing facilities. While transparent bottle-derived flakes have a higher market value, colored bottles face limited applications. The oil-trapped bottles required thorough washing before processing, leading to a huge amount of chemical usage, affecting their sustainability index. However, their recycling remains essential for sustainability, highlighting the need for improved processing technologies and market opportunities. The system boundary considered in this study is described in Figure 8.

The Functional Unit (FU) adopted in this study, as specified by the Taiwanese Environmental Protection Administration's Carbon Footprint Information Platform, is the production of one kilogram of recycled PET bottle flakes and one kilogram of recycled PET granulate. This definition enables a standardized and harmonized basis for environmental impact assessment in Taiwan. The novelty of the methodology in this research lies in its ability to aggregate environmental burdens into a single, comparable score, that being the mPt, supporting decision-making in sustainability assessment. This study follows a cradle-to-grave approach, covering key life cycle stages, from using the PET bottle to the step of forming granulates, as illustrated in the system boundary in Figure 8. However, data limitations restrict the system boundary to the collection and manufacturing stages, and the use of the cut-off approach from ISO 14040 and ISO 14044 treats plastic waste as an input material without prior environmental burdens [41]. The collection stage includes transport,

sorting, and bundling, while the manufacturing stage covers washing, shredding, drying, and pelletizing. Since Manufacturers B and C outsource pelletizing, the study is divided into two sections. The first part covers the collection stage and washing, shredding, and drying in the manufacturing stage. The second part focuses on pelletizing, which is completed only by the witness case, Plant A. This study involved a comprehensive secondary data analysis. Therefore, no primary experimental testing or laboratory preparations were conducted. This approach allowed us to evaluate the quantity of mPt produced by a PET bottle recycling facility for each FU. It provides a thorough and extensive analysis that can aid policy discussions and guide future researchers [42]. The results of this study will serve as a valuable resource for enabling mutual learning and aiming at achieving the sustainability goals in the plastic industry in Taiwan.

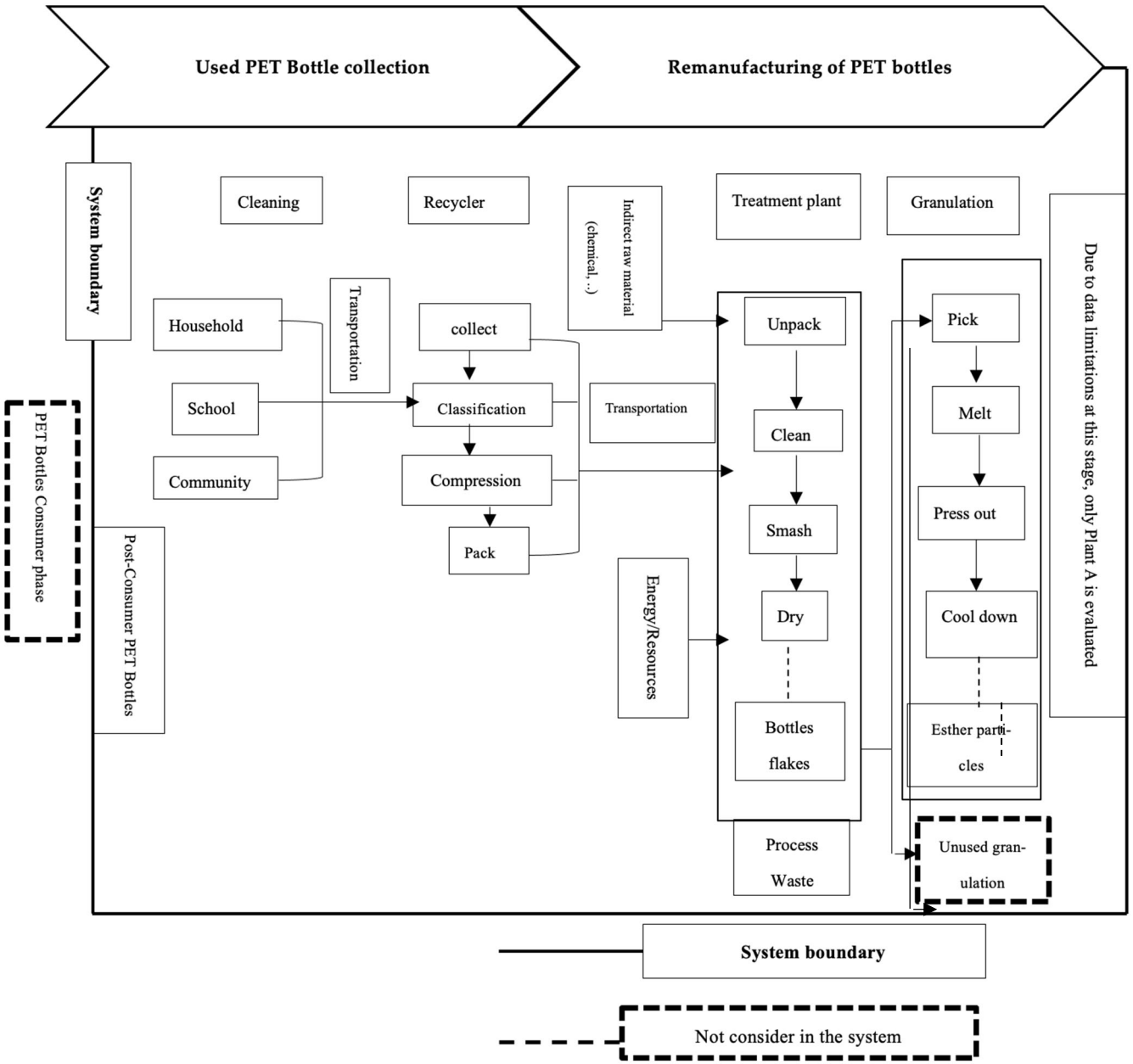


Figure 8. Research system boundary of the study.

3.2. Life Cycle Inventory Analysis and Impact Assessment

The Life Cycle Inventory (LCI) for this study was developed through data collection from PET recycling processing factories, complemented by government statistical data and sources in the literature due to the limited availability of direct operational data on the cleaning process, transport distances, and recycler internal activities. The collection phase primarily involves transporting PET waste operated by Taiwanese government recycling trucks. Taiwan's waste collection system comprises approximately 4000 routes, with an estimated total annual collection distance of 40,802,840 kilometers. Based on Taiwan EPA (2019) [43] data, the total resource recycling volume was 5,521,562 tons, with PET container recycling accounting for 107,575 tons. The transport distances for PET bottles delivered to the selected recycling plants were calculated, assuming a standard 3.5 ton light truck with a fuel efficiency of 7.79 km/L. This study assesses a recycling system with three facilities, which are as follows: Plant A (20,000 tons/year, colorless PET settled as a witness case), Plant B (15,000 tons/year, colorless PET), and Plant C (10,000 tons/year, colorful and oil-contaminated PET). The variation in processing capacity may influence each facility's energy consumption, resource utilization, and waste generation. Fuel consumption for transporting PET containers to these recycling plants and energy inputs required for processing were estimated based on official statistics and empirical data. The study also incorporates inventory data for direct and indirect raw material inputs and pollution control inputs at each Processing Plant. Specific material usage, such as cleaning agents, packaging materials, and consumables equipment, were quantified for each facility. Furthermore, detailed records of fuel, electricity, and water consumption were evaluated to facilitate an accurate assessment of environmental burdens. Finally, the waste treatment stage was analyzed, accounting for the disposal and recycling of process-generated waste, including organic sludge, mixed plastic waste, and metal scraps.

The Life Cycle Impact Assessment (LCIA) was conducted using SimaPro 9.0.0.33 software, with environmental impacts evaluated using the ReCiPe methodology, a widely recognized impact assessment framework integrating midpoint characterization factors and endpoint damage values [44]. The ReCiPe method, which requires detailed LCI, provides a comprehensive approach to quantifying environmental impacts across various categories, including human health, resource depletion, and ecotoxicity [45]. The assessment encompasses all stages of the PET recycling process, from collection and transportation to processing and waste treatment, ensuring a holistic evaluation of the environmental performance of the recycling system. Energy consumption, emissions, and waste generation were analyzed to identify key impact hotspots within the system. The indirect raw materials include cleaning agents used in the washing process, consumable equipment, and packaging materials. The pollution control inputs that focus on neutralizing wastewater to meet the pH standard comprise chemicals such as Poly Aluminum Chloride (PAC), sulfuric acid (H_2SO_4), and sodium hydroxide (NaOH). The results offer critical insights into the sustainability of PET recycling in Taiwan, supporting data-driven recommendations for optimizing resource efficiency and minimizing ecological issues on the island.

3.3. Limitations of This Study

Based on the defined scope and system boundary, the following assumptions and limitations have been adopted:

- Self-Reported Data: Inventory data were obtained through self-reporting by the manufacturer without on-site verification, limiting accuracy.
- Pre-Collection Stage Exclusion: PET waste collection distances were estimated following the Taiwanese EPA 2017 report's guidelines and adjusted based on factory-specific processing proportions [46].

- Estimated Energy Consumption: Fuel and electricity usage for transportation and recycling were based on the 2009 EPA report, with national averages applied [47].
- Environmental Burden Allocation: Only transportation and energy consumption from sanitation teams, recyclers, and recovery facilities were considered, as waste PET bears no ecological burden.
- Data Allocation for Processing Plant A: Material and energy consumption were proportionally distributed among certified PET flakes, non-certified PET flakes, and the pelletizing process.
- Pelletizing Process Assumptions: Only factory A performed internal pelletizing; therefore, data for this stage were based only on that factory's operation.
- This study primarily focuses on the environmental dimension of sustainability, excluding the economic feasibility of PET recycling. This limitation should be addressed in future research.
- The sole use of the ReCiPe methodology in this study limits its generalizability and analytical depth due to the method's qualitative and interpretive focus.

4. Conclusions

This study conducted an environmental impact assessment of Taiwanese recycled PET flakes, highlighting significant variations among three Processing Plants (A, B, and C). The results expressed in mPt allow organizations, industries, and policymakers to set thresholds for sustainability improvements. The findings from the LCA endpoint reveal that Plant A produces 18.1 mPt per FU, while Plant B generates 16.6 mPt, and Plant C has the highest output at 25 mPt. Plants A and B primarily recycle colorless PET bottles, with their environmental impact largely stemming from the manufacturing phase, particularly regarding electricity consumption and pollution control measures, including the PAC. In contrast, Plant C, which processes colored and oil-contaminated bottles, demonstrates the most significant environmental damage per kilogram of recycled PET flakes (25 mPt), mainly due to its greater wastewater treatment needs. Only Plant A conducts internal pelletizing among the three facilities for granulation, with an associated environmental damage of 34.5 mPt per FU of recycled PET pellets, primarily driven by electricity consumption. The results highlight the importance of reusing and recycling PET to reduce dependence on virgin materials. Furthermore, to reduce the impact of electricity consumption, these facilities should integrate renewable energy sources, such as solar and wind. Several policies and operational improvements are advisable to enhance the sustainability of PET recycling. Prioritizing the processing of clear PET bottles is essential, as they present a lower environmental footprint and greater market demand. Taiwan could adopt measures akin to Japan's to diminish contamination during recycling, such as mandating heat-shrink labels on PET bottles. Furthermore, implementing closed-loop water washing systems, accompanied by guidelines for monitoring and improving water recycling efficiency, can optimize water usage in bottle washing at Plant B. Additionally, Plant C should focus on reducing chemical inputs in wastewater treatment or consider using greener chemical alternatives, such as biodegradable surfactants, to enhance resource efficiency. Instead of incinerating mixed plastic waste from labels and sheets as industrial waste, it could be converted into a high-energy solid fuel for use in industrial boilers, thus replacing heavy fuel oil. Moreover, there is a need to revise regulatory restrictions on using recycled plastic in food-contact packaging. As global standards increasingly require recycled content in packaging, aligning Taiwan's regulations with these international trends will promote industry growth and support environmental sustainability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/recycling10030098/s1, Table S1: Detailed Analysis of LCA results of Plant A; Table S2: LCA Endpoint Results of Plant B; Table S3: Detailed analysis of LCA results of Plant C; Table S4: Detailed results analysis of LCA results of the pelletization; File S1: LCA Pet Bottles Recycling Plant Raw Data.

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