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Original Research

Assessing the Selection of PET Recycling Options in Japan: Multi-Criteria Decision Analysis

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Abstract

This study aims to identify the optimal Polyethylene Terephthalate (PET) recycling technique in Japan based on multi-criteria decision analysis. Eight environment, eight economy, and five social criteria were shortlisted, scored, and weighted through expert interviews. Mechanical recycling, which extrudes flakes directly into fiber, was the most preferable due to its environmental advantages (with a mean score of 0.86 out of one). Another mechanical recycling technique, which converts flakes into pellets or chips before conversion into fiber, ranked second. Gasification was the least preferred option, with a mean score of 0.57, which was largely due to negative economic effects. Nonetheless, the scoring for gasification was sensitive to changes in the importance given to the environment dimension. Depolymerization may be preferred when economic factors are prioritized. The findings provide insights into potential alternative PET recycling options in the Japanese context based on the systematic assessment of the multifaceted factors influencing the choice of PET recycling technologies. The results also emphasize the importance of selecting recycling alternatives carefully in light of the trend toward increased plastic recycling, and the need for every country to work toward circularity to reduce plastic pollution's negative impacts by increasing plastic waste recycling.

Keywords: multi criteria decision analysis, polyethylene terephthalate, plastic recycling, plastic waste management, circular economy

Introduction

Mismanaged plastic waste currently receives significant attention as it contributes to plastic pollution at the global, regional, national, and local levels. Improperly managed plastic waste leads to contamination of the air, water, and soil, causing environmental issues. Annually, the ocean receives at least eight million tonnes of plastic waste [1], which is expected to continue increasing.

Only 9% of the plastic waste worldwide is recycled. Furthermore, 22% bypasses proper waste management systems and ends up in unregulated dumpsites, or terrestrial or aquatic environments, primarily in developing nations, while 19% is burned and 50% is dumped in landfills [2]. In fact, over the forecast period, recycling rates are predicted to rise, and new markets for recycling are emerging. However, the disposal percentage is expected to remain high [3].

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One of the most ubiquitous polymers is polyethylene terephthalate (PET). It is used for food packing sheets and microwaveable food trays. Its inherent characteristics make it ideal for lightweight, high-capacity, and resistant containers, contributing to its popularity [4]. The amount of PET recycled varies by country. For example, Norway leads the global recycling trend of PET with a recycling rate of 97% for plastic bottles. In contrast, in the United States in 2018, only 29% of the plastic bottles were recycled. In 2017, Japan's PET recycling rate was 85% [5]. However, this figure includes incineration with energy recovery as recycling, and it is still debatable whether incineration with energy recovery qualifies as recycling.

Material and chemical recycling are important recycling methods for PET. In both technologies, several technological developments are taking place, though with advantages and disadvantages. Material recycling has the following key benefits. First, the procedure is simple, and it requires a low investment cost. It utilizes readily available and simple technology, causing less environmental impact. On the other hand, the drawbacks are the limits of applicable plastic wastes for recycling. For instance, the thermoset PET and contaminated wastes cannot be recycled with material recycling. In addition, degradation of recycled polymers including yellowing occurs in material recycling. As for chemical recycling, the quality of recycled PET products is maintained as shown by the constant molecular weight of recycled PET. Chemical recycling is applicable to conversion of a variety of PET wastes, including polluted and extremely complicated waste streams, into the desired product. On the other hand, the more expensive production cost of chemically reprocessed PET in contrast to virgin PET has resulted in higher manufacturing costs than material recycling. A large-scale recycling facility must be installed to benefit from the economies of scale [6].

In the selection of PET recycling options, the environmental, economic, and social factors should be considered. In other words, a "sustainability assessment" is essential. The sustainability assessment is a process of identifying, quantifying, and evaluating the possible effects of sustainability options [7]. When evaluating sustainability goals, the triple bottom line – social, environmental, and economic – should be given special consideration. The sustainability assessment's aim can be defined as "maximizing environmental, economic, and social benefits, while minimizing the negative impact" in assessing end-of-life management alternatives for PET wastes. Therefore, this study conducted in-depth discussions on environmental, economic, and social perspectives to identify the best PET waste recycling technology.

The sustainability assessment is widely applied to the selection of waste management options. First, some literature calculates a single criterion for environmental impacts. Geetha et al., Gomes et al., and Rochat et al. [8-10], for instance, choose environmental criteria such as CO_2 emissions, environmental effects, and environmental impacts. Vinodh et al. [11] include mineral and energy resources, land resources, water resources, and air resources as environmental criteria for the optimal plastic recycling methods. Deshpande et al. [12] consider energy recovery, GHG emissions, marine eutrophication, fossil fuel depletion as environmental criteria for selecting the end-of-life options for fishing gear in Norway. Using a simple criterion as those in Rochat et al. [10], Geetha et al. [8], and Gomes et al. [9] may be easier for individuals to interpret the results owing to the streamlined criteria. However, it may fail to consider some important factors without taking the desires of the stakeholders into account.

Second, regarding economic criteria, some literature considers both benefits and costs, while other literature does not. It also varies across the literature whether to consider both the capital stage and operation stage. Geetha et al. [8] consider the cost of recycling without accounting for the benefits brought by recycling. Deshpande et al. [12], for example, focus on benefits and costs at the operation stage, ignoring capital investments in determining methods for assessing the cost. Gomes et al. [9] also consider the advantages and disadvantages of capital and operating costs. Finally, Vinodh et al. [11] attempt to assess the financial situation of the recycling activities. Their findings can be claimed to reflect the actual recycling operation more accurately.

Third, existing literature uses insufficient requirements of social sustainability. For instance, Geetha et al., Gomes et al., and Rochat et al. [8-10] use a single criterion to cover social aspects: corporate image, the number of employees working to recycle 1 kg of PET each month, and safety respectively. In fact, the focus of Geetha et al. [8] is on creating decision-making models, where choosing the appropriate criteria is not their primary research goal. Their selection of social criteria can skew the outcomes of comparison of plastic waste management methods.

PET recycling practices in Japan appear to be advanced. For instance, the 2020 PET bottle recycling rate was 88.5% [13], which is significantly higher than the EU or US's respective rates of 58.2% and 28.9% in 2017 [5]. The capacity and advancement of the PET recycling system, however, can be further improved. For instance, out of the 4.88 billion tonnes of recycled PET bottles, 1.44 billion tonnes are recycled abroad [14]. Given the recent restrictions on plastic waste import in other countries [15], this situation may not be sustainable.

Japan has continued to rely heavily on thermal recovery. For example, 63% of the total plastic waste generated in Japan is burned with energy recovery, while only 8% is burned without energy recovery [16]. To create sustainable recycling systems, further development of recycling technologies such as material and chemical recycling should be promoted.

The recycled PET market is expected to increase rapidly on a global scale and gradually in Japan. In fact, the market is expected to expand at a compound annual growth rate of around 7% during the forecast period of 2021-2031, reaching a size of USD 11.9 billion by 2031 globally [17]. In Japan, some PET bottle wastes from homes are collected by municipalities and recycled after the wastes are sold at the Japan Containers and Packaging Recycling Association if the municipalities use the extended producer responsibility system. As a result, the separately recycled PET bottles within the country have increased from 261 thousand tonnes in 2015 to 344 thousand tonnes in 2020 [14]. Unlike PET bottle wastes, other domestic PET wastes are collected by municipalities with other plastic wastes or as domestic wastes without separate collection.

The recycled PET market is subject to change due to external factors. First, the demand for virgin and recycled products has significantly impacted the price of PET waste. One study on the impact of PET bottle recycling and market alternatives shows that the demand for material, regardless of being virgin or recycled, has impacted the advantage of material recycling for PET bottle wastes [18]. Second, the quality of PET waste may have directly impacted the quality of recycled products. In particular, material recycling requires high quality PET wastes with less contamination [19].

Even though many recycling options are available, selecting the optimal recycling alternative is influenced by various aspects, including the political and market conditions, which can be challenging. In this context, developing a PET decision-making assistance system based on thorough assessment of environmental, economic, and social perspectives will be valuable in providing insights for each potential alternative option. This study analyzes complex PET waste management technologies using multicriteria decision analysis (MCDA). MCDA assists in identifying the best technologies for managing PET waste and settling disputes among parties. Especially, this research aims to include a sufficient range of variables in selecting PET recycling technologies.

Materials and Methods

Multi Criteria Decision Analysis

Multiple parties are involved in decision making on plastic recycling, and thus those decisions must take different factors into account and be optimized for them. For this purpose, MCDA is a suitable analytical technique for comparing plastic recycling decision-making scenarios. First, MCDA is utilized for consensus-based decision-making while considering the opinions of a range of stakeholders [20, 21]. For instance, to develop a comprehensive and satisfactory groundwater management solution, Apperl et al. [20] examine how multi-attribute value theory (MAVT) has helped resolve conflicts in groundwater management. The outcome demonstrates difficulties in the use of MAVT to locate the optimal answer. However, MAVT was useful for identifying the project stakeholders' competing interests [20]. Generowicz et al. [22] utilized MCDA to evaluate and compare three municipal waste incineration systems in Warsaw, Tarnobrzeg, and Vienna, incorporating life cycle assessment (LCA) as part of MCDA. Their study found that the incineration technology in Vienna was the most appropriate option due to its higher capacity, lower environmental impacts, and efficient flue gas treatment systems, despite the associated high costs. MCDA can be utilized to assist and arrive at decision-making that is geared toward consensus while resolving disputes among stakeholders [21].

Second, MCDA is a feasible approach to choosing or ranking the best solutions among several alternatives while taking environmental, economic, and social factors into account in plastic waste management. For instance, MAVT-based methodologies are used to determine the best end-of-life management for fishing equipment in Norway. The recycling outcome demonstrates that the domestic recycling of fisheries has the greatest environmental, economic, and social advantages [12].

Steps Followed in MCDA

The research steps for the MCDA are shown in Fig. 1. In the first stage, secondary data were gathered to identify potential PET recycling alternatives and criteria and develop a list of potential expert interviewees. The interviews were then conducted to shortlist and weigh the criteria. The calculated weights for each criterion were used to rank the alternatives based on the MAVT. Finally, the result was evaluated while the data robustness was tested through sensitivity analysis. Each step is further described in the subsequent sections.

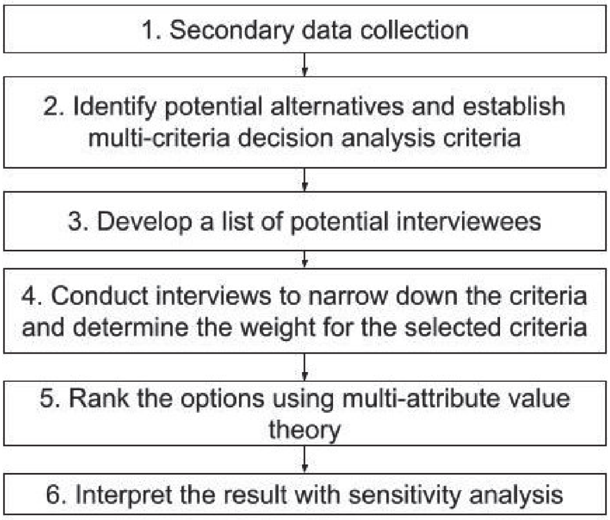

Fig. 1. Steps followed for the multi-criteria decision analysis.

Selection of Alternatives

This research focuses on PET because of the relatively well-established recycling system and technologies. There has been significant technological advancement in PET recycling [23]. Since the 1990s, advancements were made in the retrieval and recycling processes of PET [24]. Consequently, compared to other types of polymers, PET is more widely collected and recycled.

Among the numerous existing PET recycling technologies, mechanical recycling (PET bottles and other to fibers), semi-mechanical recycling (flakes to pellets/chips, and then the pellets/chips to fibers), depolymerization, and gasification were selected as an option, due to the current commercial availability (Table 1) [25, 26].

Selection of Criteria

Table 2 shows the detailed criteria for the interviews, which were composed of environmental, economic, and social criteria. The two elements were considered when selecting the environmental criteria. First, the standards for evaluating LCA were used because LCA is a prominent method for evaluating the environmental impacts of plastic waste management systems [27]. Second, some criteria were introduced as deemed necessary by the authors, to accurately reflect the operational realities of the environmental impacts of plastic waste recycling.

The following criteria were selected based on previous LCA studies: Global warming potential (GWP), Total energy demand, Acidification potential, Eutrophication potential, Photochemical oxidant formation, Abiotic resource depletion, and Solid waste generation by weight. Water consumption was also included because of its significance in cleaning plastic waste to raise recycling efficiency.

As for economic criteria, Gomes et al. [9], Valle et al. [28], and Larrain et al. [29] employ capital costs. Furthermore, MCDA analysis in waste management frequently uses operational cost [9, 28-30]. However, to clarify the actual operating situation, the operational cost was decomposed into feedstock, solid waste treatment, wastewater treatment, water, and electricity costs, and they were included as a criterion. The operational profit from the recycling business and the non-recycling business were also added to assess the profitability of the recycling activities.

Regarding the social factors, Deshpande et al. [12] conduct MCDA for fishing gear in Norway, and Rochat et al. [10] employ multi-attribute utility theory for the best scenarios for PET waste, where both studies use job creation as a criterion. Likewise, Bhagat et al. [31] consider national/local policies. Deshpande et al. [12] and Rochat et al. [10] mention the ability to manage and accept each alternative. Corporate Social Responsibility (CSR) is regarded as a crucial element for boosting recycling particularly because this leads to a rise in the consumption of recycled goods [32]. Moreover, working environments are included because employees in the recycling industry may suffer from ill health and severe biological impacts, though their exact incidence has likely not been quantified [33].

Expert Interviews

The importance of each criterion was measured in the interviews. This study used a five-point Likert scale with the following levels: extremely important, important, neutral, low important, or not at all important. The interviews included nine experts from national and local governments and 11 experts from the plastic recycling businesses. Among the 11 business experts, seven worked on material recycling, and three were involved in thermal recovery. One expert was involved in material and chemical recycling. All interviews were conducted online. The survey form was provided before the interviews, and their answered were provided during the interviews.

Ranking the Options with Multi Attribute Value Theory

The MCDA method has extensive variations applied according to respective research aims. This paper selects MAVT, which is a value measurement model in which numerical scores are created to reflect the level of a potential preference for one choice alternative over

Table 1. PET recycling technology alternatives [26, 27].

#	Name	Explanation
1	Mechanical recycling	PET waste flakes are directly extruded into fiber.
2	Semi-mechanical recycling	PET waste flakes are converted into pellets/chips, which are then converted into fibers.
3	Depolymerization	Depolymerization is a process that reverses polymerization, yielding single monomer molecules or shorter fragments that can be recombined into new polymers. A process that is the reverse of polymerization, yielding either single monomer molecules or shorter fragments that can be recombined into new polymers.
4	Gasification	Utilizing partial oxidation with air or steam enables the transformation of plastic waste into gaseous compounds in a precise and scientific context.

Table 2. Criteria list.

Perspective	#	Criteria	Details
Environmental	1	Global warming potential (GWP)	This is the warming effect on the earth's surface arising from the emission of a gas relative to carbon.
	2	Total energy demand	This is the energy usage when each alternative is implemented.
	3	Acidification potential	This is a measure of the SO2 emissions. Acidification has an important impact on marine, coastal, and freshwater habitats. Calcifying organisms, juvenile stages, and coral reefs ecosystems are particularly vulnerable to this process. Species diversity and ecosystem resilience are expected to decrease in the near future.
	4	Eutrophication potential	This indicates the enrichment of aquatic ecosystems with nutritional elements (e.g., nitrogen and phosphorus compounds). It causes excessive algae growth, which releases toxins harmful to higher energy forms, and reduces light and oxygen in the water, harming other aquatic life.
	5	Photochemical oxidant formation	This criterion can be related to air pollution. photochemical oxidant formation, (photochemical) ozone creation, or ozone formation. The photochemical oxidants are secondary air pollutants (also called summer smog) formed by the reaction of sunlight on carbon monoxide, and reactive hydrocarbons (e.g., ethane) in the presence of nitrogen oxides. It is connected in problems of smog, crop damage and the degradation of works of art.
	6	Abiotic resource depletion	Abiotic depletion refers to the depletion of nonliving (abiotic) resources such as fossil fuels, minerals, clay, and peat.
	7	Water consumption	The amount of wastewater consumption across the recycling processes.
	8	Solid waste generation by weight	The amount of solid waste across the recycling processes.
Economic	9	Capital cost	This is basically the sum of the acquisition costs and assembly of the equipment plus the costs of constructing the infrastructure needed for the operation.
	10	Operating profit from main recycling business	This is considered as the profit from selling the recycled products and gate fees in the recycling business
	11	Profit from other activities	This refers to the profit generated from non-recycling activities, such as subsidies or other unrelated business operations.
	12	Solid waste treatment cost	This cost refers to the expenses associated with managing and treating solid waste generated during the recycling process.
	13	Wastewater treatment cost	This cost refers to the expenses associated with treating and managing the wastewater generated during the recycling process.
	14	Water cost	Water is often used in recycling processes for cleaning, cooling
	15	Electricity cost	Electricity is used to power machinery and equipment in recycling facilities.
	16	Feedstock cost	Feedstock cost for the recycling
Social	17	Job creation opportunity	This refers to the employment opportunities generated by a specific management alternative.
	18	Working environment	The working environment refers to the physical and psychological aspects of a workplace that can affect employees' performance, well-being, and overall experience.
	19	Confirming to national/ local policy	This refers to the extent to which each alternative aligns with national or local policies and regulations.
	20	Capacity for managing and accepting each alternative	The ability to handle and implement different treatment alternatives, considering the resources, infrastructure, and expertise needed.
	21	Corporate social responsibility (CSR)	This refers to a company's commitment to ethical, social, and environmental responsibilities, which can include initiatives aimed at improving the well-being of communities, employees, and the planet

another (1) [21]. MAVT is an additive model, where value function $v_j(a)$ to each criterion j is summed up after it is multiplied by the k_j, or the weight for each criterion.

$$v(a) = \sum_{j=1}^{n} v_j(a)\, k_j \tag{1}$$

Analytic hierarchy process (AHP) is another common MCDA method applied in waste management. However, this study did not adopt it for several reasons as follows [34].

1. MAVT can address a large number of alternatives compared to AHP.
2. MAVT uses a utility function, whereas AHP uses the pairwise comparison. The latter can easily compare multiple objectives simultaneously.
3. For a small number of criteria, MAVT is more suitable than AHP.
4. MAVT can convert qualitative criteria into quantitative criteria.
5. Unlike AHP, MAVT utilizes a decision aid specialist who explains the criteria or alternatives to the stakeholders during interviews, which helps improve the quality of results and the reflection of their answers.

Results and Discussions

Table 3 illustrates the top 11 prioritized criteria with a standard deviation being less than one. These 11 were shortlisted as the criteria for MCDA. Table 4 displays the data used for the MCDA [35-44].

Ranking of Alternative Technologies

A linear value function was computed for each choice, following the recording of weights and the performance of alternatives based on the evaluation criteria. Using MAVT and DECERNS software, the final ranking of PET recycling options was established (Fig. 2). Depolymerization was the least preferred recycling option. On the other hand, mechanical recycling emerged as the most preferable option, followed by semi-mechanical recycling.

The ranking of gasification experienced the most significant change in the environmental criteria. The option was deemed least preferable when the environmental weight was less than 0.154. On the other hand, it became a preferred option when the weight exceeded 0.760.

Regarding the economic criteria, when the weight exceeded 0.907, depolymerization became almost as much preferable as material recycling options. Gasification was highly sensitive to changes in the weight. When the economic weight was above 0.572, it became the least preferable option. Mechanical recycling was more competitive than chemical recycling with the increase in the weight on capital costs, while chemical recycling was less competitive. An increasing weight for feedstock cost made mechanical recycling less preferable, while chemical recycling alternatives gained preference. Furthermore, semi-mechanical recycling was more sensitive to changes in the weight assigned to electricity costs compared to mechanical recycling. Finally, gasification demonstrated the least robustness regarding the operating profit from the

Table 3. Short listed criteria and weight.

Category	Criteria	Ranking	Mean	Std Dev	Weight
Environmental			4.71		0.330
Economic			4.69		0.330
Social			4.71		0.330
Environmental	Global warming potential	4	4.71	0.55	0.091
Environmental	Total energy demand	4	4.71	0.55	0.091
Economic	Capital cost	1	4.81	0.5	0.093
Economic	Operating profit from main recycling business	8	4.62	0.9	0.089
Economic	Solid waste treatment cost	8	4.62	0.79	0.089
Economic	Electricity cost	4	4.71	0.45	0.091
Economic	Feedstock cost	7	4.67	0.56	0.090
Social	Capacity for managing and accepting each alternative	1	4.81	0.39	0.093
Social	Corporate social responsibility	1	4.81	0.39	0.093
Social	Working environment	8	4.62	0.72	0.089
Social	Confirming to national/local policy	11	4.6	0.8	0.089

Table 4. Performance of recycling alternative [35-44].

Criteria	Unit	Mechanical recycling	Semi-mechanical recycling	Depolymerization	Gasification
Global warming potential	t CO2 equiv./1 t of recycled products	0.96	1.88	3.08	1.184
Total energy demand	GJ equiv./ 1 t of recycled products	13	23	51	3.62
Capital cost	1 ton/day capacity	6,000	6,000	385,000	857,000
Operating profit from main recycling business	$/kg recycled product sales	0.44	0.44	0.507	0.182
Solid waste treatment cost	$/kg	0.0021	0.0063	0.097	0.055
Electricity cost	$/kg recycled products	0.253	0.447	0.085	0.167
Feedstock cost	$/kg feedstock	0.16	0.16	▲0.431	▲0.431
Capacity for managing and accepting each alternative**	Ranking*	1	1	1	1
Corporate social responsibility***	Ranking*	1	1	2	2
Working environment ****	Ranking*	1	1	1	1
Confirming to national/local policy*****	Ranking*	1	1	1	1

*Smaller is better **This research estimates no significant differences were found in the required management capacity for each alternative option. As a result, all options are assigned a score of 1. ***Due to the low public perception of chemical recycling [38] and the easier comprehension of material recycling, material recycling options are given a score of 1 for CSR, while chemical recycling options receive a score of 2. ****This study estimates that Japan does not perceive any differences in the working environment among recycling technologies. ***** Except in specific situations, such as a lack of nearby material or chemical recycling facilities, the government recommends the use of material and chemical recycling [41]. However, no priority exists between material and chemical recycling,

recycling business. When the economic weight came close to one, the option was much less attractive.

The order of recycling gasification and semi-mechanical recycling shifts if the weight assigned to social criteria is below 0.263, with gasification gaining priority. Aside from the change in ranking between semi-mechanical recycling and gasification recycling at the weight of 0.158, the ranking remains stable for the working environment.

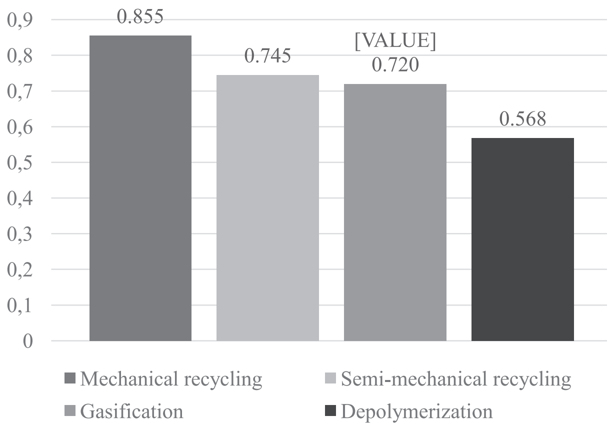

Fig. 2. Mean scores of PET recycling alternative technologies.

Discussions

The selection of appropriate recycling technology is contingent upon various factors, including the physical properties of the target components and products, the volume and frequency of collection, the intricacy of components and product structure (pertaining to production and quality management), the intended application of the product (product specifications), market considerations (demand, pricing), and the overarching management strategy (CSR and environmental management, among others) [45]. Table 5 presents the current case study for each technology in Japan [46-50]. The optimal scenario for material recycling, which encompasses both mechanical and semi-mechanical recycling processes, aligns with the current state of plastic waste recycling in Japan. At present, 1.73 million tonnes of plastic waste undergo material recycling, whereas a mere 0.27 million tonnes are addressed through chemical recycling methods [16].

Material recycling options are preferable to alternative chemical recycling solutions if GWP is more stressed. This is aligned with the result from the study which evaluates the environmental impacts of PET recycling technologies, namely, material recycling of PET bottles and Glycolysis and Methanolysis, where the LCA result for one tonne of recycled PET fiber based

Table 5. Recycling factories for polyethylene terephthalate in Japan [46-50].

Technology	Company	Description
Material recycling (PET to flake to PET)	Kyoei Sangyo Co., Ltd, Suntory Holdings	"Flake to Preform direct recycling technology" that reduces environmental impact and improves recycling efficiency by eliminating some PET bottle recycling processes. The first line was put in operation in 2018.
Semi-material recycling (PET to pellet to recycled products)	Kyoei Sangyo Co., Ltd	After the PET was converted into flakes, impurities inside the flakes are removed using a recondensation polymerization apparatus. Subsequently, the flakes are transformed into pellets with the help of an extrusion device.
Depolymerization	JEPLAN, INC.	The IS method, which involves depolymerizing PET into mono-ethylene glycol under high-temperature conditions, is being used.
Gasification	JGC Group	The technology gasifies waste plastics and converts them into syngas that can be used in chemicals and chemical products such as methanol, ammonia, propylene, and olefins, making it possible to recycle even hard-to-recyclable plastics mixed with dirt and impurities into chemical raw materials equivalent to petroleum-derived virgin products.

on the cut-off approach indicates that material recycling alternatives show less GWP than chemical recycling [26].

The greater weight of GWP favored gasification in this analysis. In fact, in the LCA of container and packaging plastic recycling in Japan, the maximum reduction effect is achieved through gasification. This is followed by recycling methods that substitute coal, such as conversion into blast furnace reductant, coke oven chemical feedstock, cement raw fuel, and Refuse-Derived Fuel [51].

Economically, the weight beyond 0.907 made depolymerization comparable to material recycling options. According to literature [52], however, a weakness of the depolymerization method is its high cost, which is due to the necessity of two processes, depolymerization and repolymerization, in the recycling procedure. The observed discrepancy suggests that the current MCDA may not accurately represent the actual situation, as it may potentially overlook crucial components influenced by stakeholders' viewpoints throughout the decision-making process. This concurs with the constraints of MCDA outlined by Talukder & Hipel [53].

Chemical recycling appears to be hindered by capital costs. However, it benefits from feedstock and electricity costs during the operation. Nikiema & Asiedu [40] note high implementation costs as a restriction to chemical recycling while attributing material recycling's drivers to their affordability. Therefore, if chemical recycling is to be promoted, strong support for the initial investment will be required.

The relationship between feedstock cost and the competitiveness of material and chemical recycling is well-established in the literature. In fact, the ability to manage lower-quality (contaminated or mixed plastic) materials is a strength of chemical recycling as compared to material recycling [25]. Gasification may be less appealing primarily due to the high initial capital costs. Nonetheless, the capacity to handle a broad array of plastics simultaneously may be undervalued, considering the numerous gasification projects in existence [54].

The outcome was not largely affected by the social criteria presumably because it is difficult to measure the criteria. Based on Jones [38], this study reveals that chemical recycling alternatives receive lower scores of CSR than material recycling alternatives. However, if the perception of CSR against each recycling is clear, inclusion of CSR as a variable for the selection of PET recycling alternatives would be beneficial. The implementation of CSR would yield optimal results to minimize the marine plastic pollution when integrated with enabling governance structures [55].

Conclusion

This paper evaluates the selection of PET recycling technologies in Japan by addressing the triple bottom line factors and utilizing the MCDA approach to ascertain the optimal PET recycling method. It was found that mechanical recycling was preferable to semi-mechanical recycling, gasification, and depolymerization.

This study, however, has several limitations. First, the input data on plastic recycling contain the system boundary. For instance, the steps of collection are not included in the data. As a result, the numerous environmental and economic effects, such as the impacts of separate collection affecting material recycling are not considered. Second, the input data originate from a variety of countries due to the limited availability of the data. The data may be affected by the large regional differences in the cost of power, for instance. Therefore, the data should ideally come from the same area. Third, the stakeholder interviews did not represent all stakeholders participating in recycling activities. The two stakeholders who were given the most consideration during the interviews were the government and recyclers. The actual decision-making process involves the community and other stakeholders. Despite these limitations, this study offers important insights, especially into choosing the best recycling techniques. For future research, it is suggested to incorporate more detailed, context-specific input data for each recycling technology alternative, engage a diverse range of logically selected stakeholders in interviews, and enhance the quantification of social indicators.

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Conflict of Interest

The authors declare no conflict of interest.

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