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Environmental Burden of Household Plastic Waste Management under Municipality-Level Policy Adaptation: a Case Study of Okayama City, Japan

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Plastic waste management has become a critical global environmental issue due to the slow degradation of plastics and the release of microplastics and harmful chemical additives. Among the available treatment methods, recycling is the most widely adopted in developed countries, offering a pathway to reduce virgin plastic production and its associated environmental impact. In Japan, municipal policies have a significant influence on household plastic waste treatment. Since March 2024, Okayama City has implemented a new policy introducing separate collection and intermediate processing of plastic resources for recycling. The environmental implications of this policy remain unclear. Existing literature consistently indicates that recycling outperforms incineration in most impact categories. Nevertheless, gaps remain in assessing the impacts of transportation and intermediate processing. To address these limitations, this study analyses four scenarios based on different collection rates and treatment options using the Life Cycle Impact Assessment (LCIA) Method based on Endpoint Modelling, tailored for the Japanese context. The results highlight that incineration imposes the greatest overall environmental burden, while recycling remains the least impactful. Recycling has the lowest damage potential to biodiversity, with the value 1×10^{-11} EINES, whereas incineration has the highest damage potential, with a value of 1×10^{-9} EINES. The findings aim to clarify the environmental burdens associated with plastic waste treatment in Okayama City and provide more sustainable waste management strategies. With the support of policy enforcement in Okayama City, recycling is the preferred pathway for plastic waste management.

1. Introduction

Plastics degrade slowly in the environment and may release microplastics or harmful chemical additives (Habuer et al., 2024). The final fate of plastic has emerged as a global environmental concern. Although incineration and landfilling are common disposal methods, recycling remains the predominant approach for plastic waste treatment in developed countries. Recycling involves recovering and reprocessing plastic waste into useful products, thereby reducing the demand for virgin plastic production and mitigating environmental impacts. Recycling methods are generally classified into four categories. First, mechanical recycling involves sorting, cleaning, shredding, melting, and reforming plastics into new products. Second, chemical recycling breaks down plastic polymers into their original monomers or smaller chemical building blocks through chemical reactions. Third, energy recovery incinerates plastic waste to generate heat or electricity. Fourth, feedstock recycling converts plastic waste into basic hydrocarbons, oils, syngas, or fuels through processes like pyrolysis, gasification, or hydrogenation (Mong et al., 2024). The segregation and final treatment of household plastic waste vary depending on municipal policies in Japan. Since March 2024, Okayama City has implemented a dedicated weekly collection system for “plastic resources”, separate from general burnable waste, to promote recycling (OCEBRRPO, 2024). Before this policy, all household plastics except for Polyethylene Terephthalate (PET) bottles were incinerated with energy recovery. Under the new system, household plastic waste is transported to a specialized intermediate processing facility established in December 2023. Plastics are shredded and sorted according to their types, followed by automated separation techniques, such as weight-based sorting, air classification, and magnetic separation, and manual sorting to remove contaminants. The processed plastics are then compressed into bales for shipment to recycling facilities. While this new policy aims

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to enhance plastic recycling, the environmental implications of household plastic waste segregation and treatment in Okayama City remain uncertain. Identifying the environmental burdens associated with various treatment options is therefore crucial. Existing literatures emphasize that each plastic waste treatment method has inherent trade-offs, and no single approach is universally sustainable. According to a Life Cycle Assessment (LCA) study, the chemical recycling of mixed plastics that are unsuitable for mechanical recycling can reduce CO_2 emissions by up to 50 % compared to incineration with energy recovery (William et al., 2023). Similarly, Eduardo et al. (2021) evaluated nine scenarios for PET bottle disposal in Bauru, Brazil, concluding that recycling consistently outperforms incineration across multiple environmental impact categories. These studies converge on the conclusion that recycling offers greater environmental benefits. However, outcomes may vary depending on scenario boundaries and methodological assumptions. Previous studies often lacked detailed analysis of impact categories such as transportation and intermediate processing. To date, no comprehensive LCA has been conducted on municipal-level household plastic waste management in Japan. These factors may result in an underestimation of the associated burdens. In this context, the present study analyses four scenarios based on varying bulk collection rates and treatment options, incorporating detailed transportation routes, the substitution effects of recycled resin, and intermediate processing within the system boundaries. The LCIA Method based on Endpoint Modelling, version 2 (LIME 2), a framework specifically developed for the Japanese context and well-suited for evaluating plastic waste management in Okayama City, was employed for this analysis. This study represents the first environmental impact assessment conducted for Okayama City following the implementation of its new household plastic segregation and recycling policy.

2. Methodology

This study focuses on Okayama City, located in Okayama Prefecture, Japan. As of 2024, the city had an estimated population of approximately 696,000 residents distributed across 340,000 households (OCGS, 2024). In terms of household waste generation, Okayama City reported a relatively low figure of 453 g/person/day, with plastic waste accounting for 17 % of the total (OC, 2022), compared to the national average of 496 g/person/day (MoEJ, 2022). For recycling rates, the national average was 19.6 %, whereas Okayama City recorded a lower rate of 13.5 % (MoEJ, 2022).

2.1 System boundary

The system boundary of this study is illustrated in Figure 1. The functional unit is defined as 1,000 kg of household plastic waste. The input consists of 1,000 kg of discarded household plastic waste, and the output is 617 kg of plastic resin, either recycled or produced from virgin materials. The substitution ratio between recycled and virgin plastic resin is assumed to be unity. Before 2024, household plastic waste in Okayama City was incinerated as combustible waste. Following the enactment of the Plastic Resource Recycling Promotion Act in Japan in 2022, a bulk plastic resource collection system (hereafter referred to as “bulk collection”) was implemented in Okayama City in March 2024. Under this system, all household plastic waste is required to be collected for recycling as a priority over incineration. Currently, household plastic waste in Okayama City is collected by contractors appointed by the municipal government and transported to an intermediate processing facility for preliminary sorting and compression (see Figure 1). Non-conforming materials identified during the rough sorting process are sent to an incineration facility for final disposal. The remaining bales are transported to recycling companies for mechanical recycling. According to the Inventory Database for Environmental Analysis (IDEA), it is estimated that 68.9 % of the baled material can be mechanically recycled into resin.

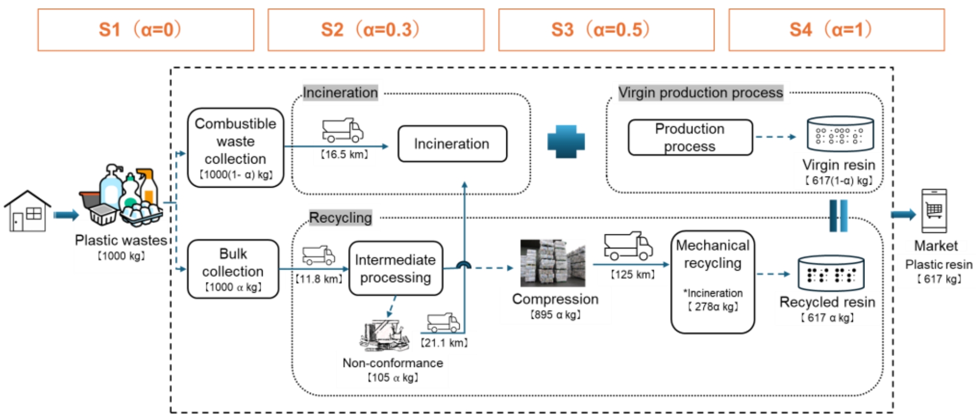

Figure 1: System boundary in this study

2.2 Scenario setting

To clarify the environmental impacts associated with different treatment options, this study establishes four scenarios based on the bulk collection rate (denoted as *a*). In scenario 1 (S1), when the bulk collection rate (*a*) is 0 %, all household plastic waste is collected as combustible waste for incineration. To meet the output requirement, [617 × (1 − *a*)] kg of virgin resin must be produced. Thus, the total output includes 1,000 kg of incinerated waste and 617 kg of virgin resin production. In scenario 2 (S2), 70 % of household plastic waste is incinerated, and 30 % is collected through the bulk collection system for recycling. Consequently, [617 × (1 − 0.3) = 431.9] kg of virgin resin is required to meet the output. The total treatment involves 700 kg incinerated, 300 kg recycled, and 431.9 kg of virgin resin production. In scenario 3 (S3), half of the household plastic waste is incinerated, and the other half is recycled via bulk collection. Accordingly, [617 × (1 − 0.5) = 308.5] kg of virgin resin is required. The total output comprises 500 kg incinerated, 500 kg recycled, and 308.5 kg of virgin resin production. In scenario 4 (S4), all household plastic waste is collected through the bulk collection system for recycling, eliminating the need for virgin resin production. Thus, the entire 1,000 kg is allocated to recycling (Table 1).

Table 1: Input and output in four scenarios (Unit: kg)

Input	(1000.0)→	S1 (*a*=0 %)	S2 (*a*=30 %)	S3 (*a*=50 %)	S4 (*a*=100 %)
Output	Incineration	1000.0	700.0	500.0	-
	Virgin production	617.0	431.9	308.5	-
	Recycling	-	300.0	500.0	1000.0

2.3 Life cycle inventory

A Life Cycle Inventory (LCI) is a fundamental component of an LCA, involving the collection and quantification of inputs and outputs across its entire life cycle. In the study, the LCI would document all the environmental flows for each of the four scenarios, including material inputs, i.e.1,000 kg of household plastic waste (as the functional unit), virgin resin production 617 × (1 − a) kg (varies by scenario), energy inputs, i.e. energy used for collection, transportation, sorting, compression, incineration, and recycling processes. Outputs include recycled plastic resin (68.9 % of bulk-collected waste becomes recycled resin), CO_2, NO_x, dioxins from incineration, emissions from mechanical recycling, residuals from recycling, ash, and non-recyclables sent to landfill or further treatment.

2.4 Life cycle impact assessment

LCIA is the next phase following the LCI. It translates the quantified inputs and outputs from the LCI into potential environmental impacts. The goal is to understand the magnitude and significance of those impacts across different categories. In this study, the LCIA would assess how each scenario affects key environmental impact categories. The software "MiLCA version 2.3" was used, which is a support system for implementing LCA for Japanese cases. It involves an inventory database IDEA, with background data on over 4,400 processes. LIME 2 is developed specifically for Japan, making it particularly suitable for this study on plastic waste in Okayama City. LIME 2 is a Japanese LCIA method that translates environmental burdens into monetary values (yen) based on their impact on human health, biodiversity, primary production, and social assets (Figure 2). It is designed to support decision-making by expressing complex environmental impacts in a single, understandable unit (Itsubo and Inaba, 2010). Key features of LIME 2 include converting 15 midpoints including Climate Change (C1), Resource Consumption (C2), Waste (C3), Ecotoxicity (Hydrosphere) (C4), Ecotoxicity (Terrestrial) (C5), Land Use (C6), and Urban Air Pollution (C7), etc. into 4 endpoints, such as human health, biodiversity loss, loss of ecosystem services, and damage to social assets. The impacts are then converted into Japanese yen (¥) using willingness-to-pay or damage cost approaches.

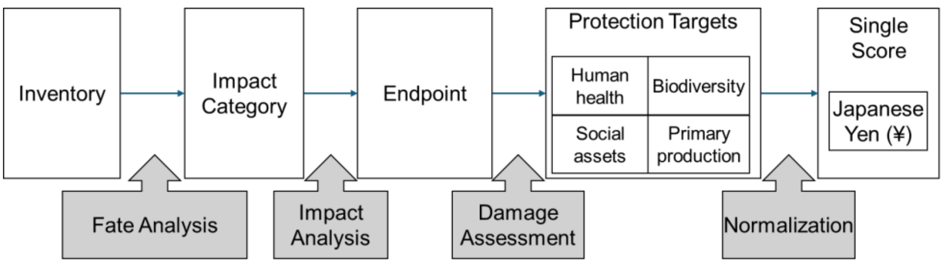

Figure 2: Conceptual framework of LIME 2

3. Results and discussion

3.1 Life cycle inventory results

In the LCI, data were collected from various processes, including incineration, virgin plastic production, intermediate processing, and mechanical recycling (Table 2). The primary data for the intermediate processing stage were obtained from an intermediate processing facility located in Okayama City, Japan. Specifically, processing 1,000 kg of discarded household plastic waste required 46.6 kWh of electricity, 1 m^2·year of land use, 0.02 m^2 of forested land converted to building land, and 3.39 liters (L) of light oil. The outputs of this process included 895 kg of compressed bales suitable for recycling and 105 kg of non-conforming materials designated for final treatment. Background data for the incineration, mechanical recycling, and virgin plastic production processes were sourced from the IDEA database, the default LCI database in MiLCA, developed by the National Institute of Advanced Industrial Science and Technology and the Japan Environmental Management Association for Industry. For transportation processes, background data corresponding to truck transport services (2 t capacity, 100 % loading rate) were applied in this study.

Table 2: Inventory results of the plastic incineration, virgin production, and recycling processes

Input & Output		Unit (1,000 kg)	Incineration	Virgin production	Recycling: Intermediate processing [1]	Recycling: Mechanical recycling
Input	Plastic waste	kg	1.00×10^{3}		1.00×10^{3}	
	Water supply	m^3	1.42×10^{0}			7.54×10^{-1}
	Landfill treatment	kg	2.13×10^{1}			9.42×10^{1}
	Ferric chloride	kg	6.00×10^{2}			
	Heavy oil C	L	1.85×10^{-1}			
	Hydrochloric acid, 35 %	kg	1.50×10^{-2}			
	Slaked lime	kg	1.11×10^{1}			
	Polyaluminum chloride	kg	8.25×10^{-1}			
	Sodium hydroxide	kg	6.00×10^{-2}			
	Electricity	kWh	3.21×10^{1}		4.66×10^{1}	6.09×10^{2}
	Land use	m^2year	2.23×10^{-1}		1.00×10^{0}	1.00×10^{0}
	Forest → Building land	m^2	4.46×10^{-3}		2.00×10^{-2}	2.01×10^{-2}
	Light oil	L			3.39×10^{0}	
	Bale	kg				1.45×10^{3}
	Groundwater	m^3				1.62×10^{0}
	Polypropylene	kg		2.46×10^{2} [a]		
	Vinyl chloride resin	kg		1.59×10^{2} [a]		
	Polystyrene	kg		8.43×10^{1} [a]		
	Polyethylene terephthalate	kg		5.72×10^{1} [a]		
	Other plastics	kg		4.54×10^{2} [a]		
Output	$PM_{2.5}$	kg	7.50×10^{-1}			
	Sulfur oxides (SO_x)	kg	5.30×10^{-4}			
	CO_2	kg	2.94×10^{3}			
	NO_x	kg	1.68×10^{0}			
	Hydrogen chloride	kg	2.40×10^{-3}			
	Bale	kg			8.95×10^{2}	
	Non-conforming materials	kg			1.05×10^{2}	4.50×10^{2}
	Recycled plastic resin	kg				1.00×10^{3}
	Virgin plastic resin	kg		1.00×10^{3}		
Transportation		km	1.65×10^{1}		1.18×10^{1}	1.25×10^{2}

[1] Data source: Intermediate processing facility in Okayama city, Japan; [a] Remain upstream processes

3.2 Life cycle impact assessment results

The aggregated impact assessment results of S1-S4 are presented in Figure 3 (a). No impacts were observed in the categories of noise and indoor air pollution. Among the 15 impact categories observed, categories C1 through C7, namely, Climate Change, Resource Consumption, Waste, Ecotoxicity (Hydrosphere), Ecotoxicity (Terrestrial), Land Use, and Urban Air Pollution, showed relatively significant impacts (Figure 3a). In contrast, categories such as Photochemical Oxidants, Acidification, Ozone Depletion, Eutrophication, Ecotoxicity (Atmosphere), and Human Toxicity exhibited comparatively low impact levels. Normalization results indicate that, except for C3, all environmental impacts exhibit a decreasing trend from S1 to S4, suggesting that recycling consistently outperforms incineration across multiple impact categories. In the Waste Impact category (C3), where landfill volume is used as the indicator, incineration exerted a lower impact on landfill space compared to recycling processes. It is because the incineration pathway occupies less land space than recycling in Japan. The incineration of plastic waste (S1) was associated with higher impacts in several categories, particularly C4, C1, and C5. These findings are consistent with previous studies (Eduardo et al., 2021). Ecotoxicity (Hydrosphere) (C4) showed the highest impact across scenarios S1 to S3, primarily due to the use of harmful chemicals in incineration and virgin resin production, as well as the environmental burden from fly ash, bottom ash for landfilling, and wastewater treatment. S4 demonstrated comparatively lower impacts in categories C2, C4, C5, and C7 (Figure 3b). In light of the substantial environmental impacts associated with climate change and ecotoxicity, recycling at least partially should be prioritized over incineration as an optimized strategy for managing household plastic waste. The damage assessment results for protection targets are presented in Figure 4.

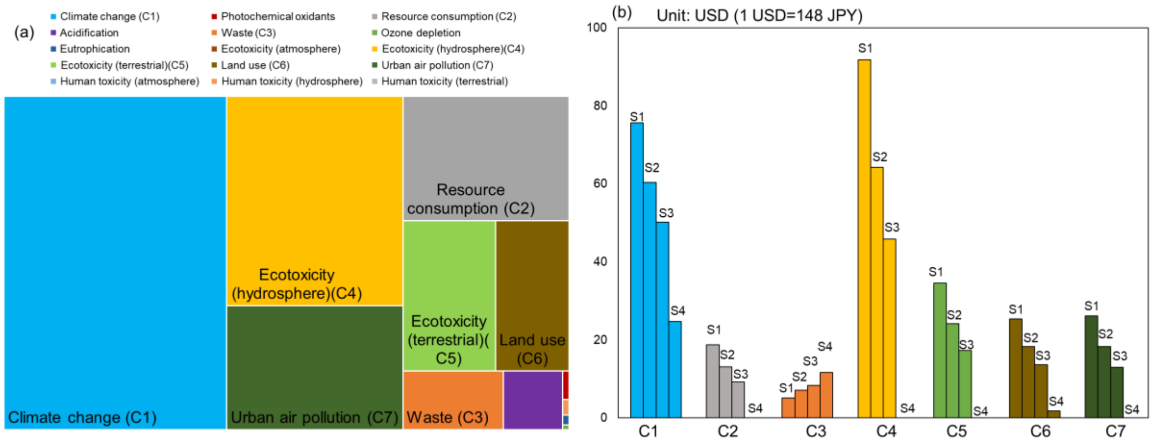

Figure 3: The characterization of impact analysis shown as a (a) Tree map and (b) Comparison of scenarios

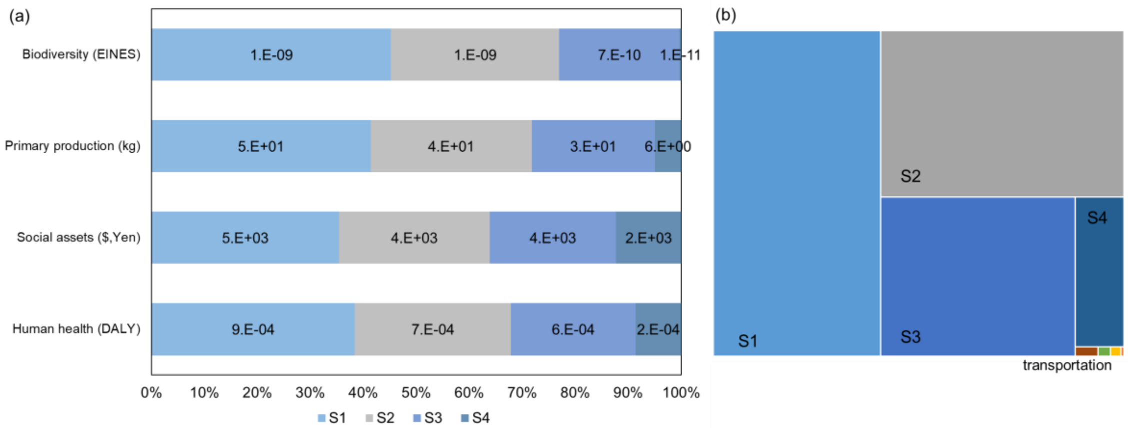

Figure 4: The damage potentials shown as (a) Protection targets by scenarios and (b) Tree map

S4 exhibited the lowest damage potential to biodiversity, with a value of 1×10^{-11} EINES (Expected Increase in Number of Extinct Species), while S1 showed the highest damage potential, with a value of 1×10^{-9} EINES

(Figure 4a). EINES is a quantitative indicator that estimates the number of additional species likely to become extinct due to environmental burdens associated with specific processes. Regarding impacts on human health, S1 had the highest damage potential, with a value of 9×10^{-4} DALY, whereas S4 showed the lowest, at 2×10^{-4} DALY. DALY (Disability-Adjusted Life Year) is commonly used to quantify the total disease burden (Habuer et al., 2021), and it is adapted to represent the long-term health effects. Normalization to a single aggregated result, as illustrated in the tree map (Figure 4b), further emphasizes that S1 imposes the highest overall environmental burden, while S4 exhibits the lowest. Changes in the collection rate, for example, 30 % in S2 and 50 % in S3, result in only marginal reductions in damage potentials, suggesting that virgin plastic production remains a major contributor to overall environmental impacts. These findings underscore the urgent need to reduce virgin plastic production and to promote recycling technologies. In contrast, transportation processes were found to contribute relatively minor environmental burdens across all scenarios.

4. Conclusion

This study evaluates four scenarios based on varying collection rates and treatment methods. The results indicate that recycling plastic waste has significantly lower environmental impacts. In contrast, incineration exhibits higher impacts across multiple categories. Recycling demonstrates the lowest damage potential to biodiversity, with a value of 1×10^{-11} EINES, while incineration shows the highest damage potential at 1×10^{-9} EINES. When normalized to a single aggregated indicator (monetary value), incineration imposes the greatest overall environmental burden, whereas recycling emerges as the least harmful option. Although recycling proves to be an environmentally preferable alternative, its successful implementation requires further efforts, particularly in promoting source separation at the household level to enhance collection rates. Changes in the collection rate led to only marginal reductions in overall damage potentials. These findings provide valuable insights into the environmental burdens associated with plastic waste segregation and treatment in Okayama City, highlighting the urgent need to reduce virgin plastic production, phase out incineration, and advance recycling technologies. Moving forward, a multi-dimensional assessment encompassing environmental, economic, social, political, and technical aspects will be essential to support sustainable decision-making.

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