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Assessing Plastic Waste Green Economy Management via Integrated Life Cycle Environmental and Costing Framework

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Plastic waste (PW) mishandling is an ever-growing global conundrum that can negatively impact the environment and human health. A circular plastic economy is introduced for a sustainable systemic transition in the PW value chain. Nevertheless, life-cycle circularity in PW management remains flawed in various countries, especially when issues such as economic loopholes, externality cost negligence, and free-ridership exist in the PW value chain. To date, research conducted on scientific and standardized methodologies for circular PW management is rare. In this study, an integrated life cycle assessment (LCA) and life cycle costing (LCC) methodology with two novel performance indicators: PW footprint and life cycle benefit-cost ratio (BCR) are introduced to measure the sustainability of PW management. Based on the integrated LCA-LCC methodology, the mechanical recycling pathway exhibits outstanding environmental (59-88 % environmental saving) and economic performance (412.70 $US\$_{2022}$ t^{-1} PW) with and without externality cost consideration among incineration and landfilling pathways. The research outcomes of this study shall provide scientific and green economy insights to PW value chain stakeholders in circular plastic management.

1. Introduction

Global plastic waste (PW) amounted to 2.38×10^8 t by 2019 and is estimated to peak at 4.08×10^8 t by 2040 (UNEP, 2023). Due to the single-use nature and non-biodegradability of plastics, PW mismanagement harbours persistent environmental and human health threats with long-lasting consequences (Chin et al., 2022b). Disrupted global PW flow from the import ban in China was diverted to Southeast Asian (SEA) countries such as Malaysia, leading to PW overspill in those countries. Despite exploring various trailblazing PW treatment technologies (i.e., physical, biochemical, thermos-chemical processes), majority of the developed countries still discard most of PW in landfills (Geyer et al., 2017) because those technologies are at a nascent stage and obstructed by economic hurdles. The circular plastic economy concept is introduced (WEF, 2016) to dampen those challenges, minimize the environmental burden from PW and realize closed-loop recycling. With the implementation of a circular plastic economy under the Extended Producer Responsibility (EPR) scheme, less cost-extensive PW treatment technologies such as mechanical recycling, incineration and pelletization are slowly merging into the PW management system of different countries. Although the circular plastic economy diffuses part of global PW streams away from landfills, the circular systemic changes of the PW economy are approaching a stagnant point because of the severe lack of generally-accepted and standardized scientific instrument or indicator to conduct a combinatorial assessment of PW economic and environmental performance with externality consideration (Mulya et al., 2022). Past research limitations of LCA and LCC on the PW economic and environmental performance include: (a) emphasizes only the environmental assessment, (b)

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considers only budget cost in the life cycle costing, and (c) includes merely climate change for externality costing. Civancik-Uslu et al. (2019) conducted a LCA merged with the eco-design concept and revealed that materials substituting virgin plastic in cosmetic packaging could reduce overall environmental burdens by 12 %, but the economic feasibility of the eco-designs is not analyzed. Exploring the end-of-life options ranking for PW from fishing gears, Deshpande et al. (2020) concluded that recycling thrives over incineration and landfilling with better environmental and economic efficiency but without considering externality cost. Cornago et al. (2021) concluded that the gr3n scheme should be implemented for the chemical recycling of PET but involving only budget cost for economic assessment. Though assessed both budget and externality costs imposed for PET recycling to produce blankets, Zhang et al. (2020) discussed both costs separately without making a direct comparison. Talang and Sirivithayapakorn (2021) combined the assessment of budget and externality costs for municipal solid waste management, but PW is classified as combustibles and can only be sent to incineration in the proposed management schemes. Among the common research gaps identified from the discussed studies is the absence of performance indicators which can simultaneously compare the economic and environmental performance of PW management systems under the circumstances with or without externality cost. Another research gap is the absence of externality cost in benefit-cost ratio (BCR) analysis for different PW treatment pathways (e.g., recycling, landfilling), which can quantify the green economic feasibility of the secondary products resulting from PW management. To counter the research gaps, both novel green PW economic indicators (i.e., PW footprint and life-cycle BCR) are introduced under an integrated LCA-LCC framework.

2. Integrated Life Cycle Circularity Framework for Plastic Waste Management

The integrated framework is a combined methodology of life cycle environmental assessment (LCA) and life cycle costing (LCA) with externality cost consideration in PW management (Figure 1). Both LCA and LCC conducted in this study adhere to the standard requirement outlined in ISO14040 and ISO14046. Phase 1 (LCA) of the integrated framework comprises four key stages: (1) Goal and scope definition, (2) Life cycle inventory, (3) Life cycle impact assessment, and (4) Life cycle interpretation. Meanwhile, Phase 2 (LCC) aligns with the crucial stages in Phase 1 regarding economic components (i.e., budget and externality costs). Unlike conventional economic system modelling, the life cycle costing in this study proposes two main PW circular economy indicators: PW footprint and life-cycle BCR.

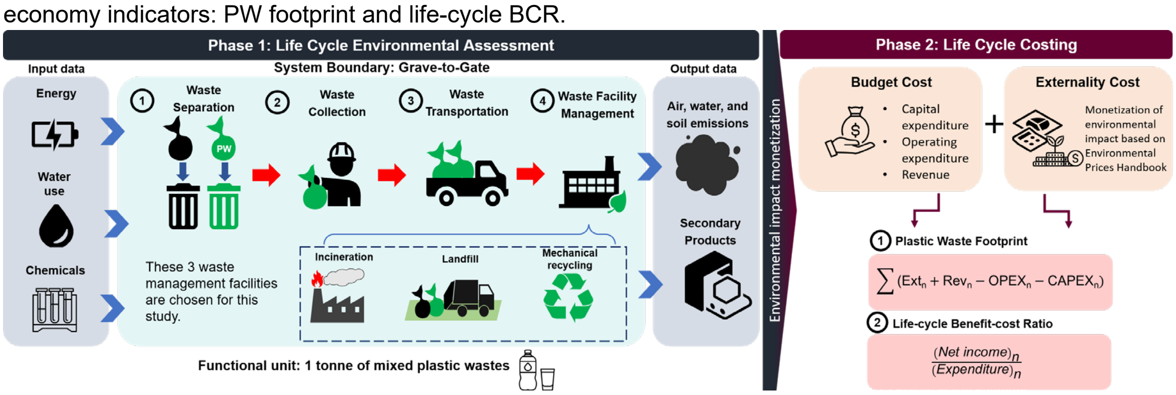

Figure 1: Integrated LCA-LCC framework for circular PW management

2.1 Phase 1: Goal and scope definition

Figure 1 illustrates the significant stages in PW management considered for the "grave-to-gate" system boundary of this study, namely waste separation, waste collection, waste transportation, and waste facilities (i.e., incineration, landfilling, and mechanical recycling). The upstream processes (e.g., virgin material production and transportation) of PW management are excluded from the system boundary because the PW management value chain itself is as complicated as the upstream value chain. Malaysia, one of the top PW export destinations in the SEA region, is selected as the case study. The functional unit determined for this study is 1 t of mixed PW (i.e., 26 % polypropylene, 24 % low-density polyethylene, 22 % polyethylene terephthalate, 13 % polystyrene, 10 % polyvinyl chloride, 3 % others, 2 % high-density polyethylene). Only three PW management facilities are chosen for this study because the selected PW facilities are the primary PW management pathways worldwide (OECD, 2018).

2.2 Phase 1: Life cycle inventory

Data sources are primarily extracted from local governmental reports, ecoinvent 3.0 database and literature from high-impact factor journals. The input and output data of all significant stages in the system boundary are energy consumption and loss, water usage, chemicals utilization, emissions (i.e., air, water, and soil), and secondary products recovered from PW. The avoided impact resulting from the secondary products is accounted for further assessment. Landfills are assumed to be built 5 km from the residential areas while incinerators and mechanical recycling plants are assumed to be 10 km, in which the facilities have a life span of 20 y (Lin et al., 2022). Budget cost data are mainly collected from governmental reports. Table 1 demonstrates the data inventory for this study.

Table 1: Data inventory for material flow and budget cost of PW management system

Data types	Unit per t PW	Data references
Incineration		
Amount of electricity produced	1,180 kWh	ecoinvent database (mixed PW)
Amount of heat	8,220 MJ	ecoinvent database (mixed PW)
Amount of bottom ash	0.04 t	ecoinvent database (mixed PW)
Operating cost	15.23 $US\$_{2022}$	PEMANDU (2015)
Capital cost	11.25 $US\$_{2022}$	PEMANDU (2015)
Revenue from electricity	56.00 $US\$_{2022}$	SEDA (2022)
Revenue from bottom ash	3.17 $US\$_{2022}$	Pricing survey from online websites
Gate fee	20.96 $US\$_{2022}$	The Star (2017)
Mechanical recycling		
Recycled plastics	0.60 t	Chew et al. (2022)
Operating cost	3.71 $US\$_{2022}$	PEMANDU (2015)
Capital cost	2.06 $US\$_{2022}$	PEMANDU (2015)
Revenue from recycled plastic	410.80 $US\$_{2022}$	MPMA and MRMA (2019)
Landfills (including sanitary landfills)		
Amount of electricity produced	23.1 kWh	ecoinvent database
Operating cost	5.79 $US\$_{2022}$	PEMANDU (2015)
Capital cost	0.25 $US\$_{2022}$	PEMANDU (2015)
Revenue from electricity	0.70 $US\$_{2022}$	SEDA (2022)
Gate fee	6.27 $US\$_{2022}$	PEMANDU (2015)

2.3 Phase 1: Life cycle impact assessment

ReCiPe 2016 characterization method from SimaPro software 9.0 is applied for life cycle environmental impact assessment. The method assesses the PW management system with three different pathways (i.e., landfilling, incineration, and mechanical recycling) under eighteen impact categories and three damage categories (i.e., human health, resource scarcity, and ecosystem quality).

2.4 Phase 2: Life cycle costing

Details of PW management system budget cost are listed in Table 1. The externality cost (i.e., expected economic welfare loss or gain when one additional kg of the pollutant enters the environment) of the PW management system is calculated based on the shadow pricing compiled in the Environmental Prices Handbook (EPH) initiated by the CE Delft for externality fiscal planning (de Bruyn et al., 2018). Each environmental impact is factored with a specific externality cost provided in the EPH. The obtained LCA results are monetized based on the handbook's externality cost factors. The advantage of using the EPH to speculate the externality cost rising from environmental impact is that the environmental impact included for shadow pricing in this guideline coincides with the impact categories in ReCiPe 2016 characterization method.

2.5 Phase 1: Life cycle interpretation

Scenario analysis examines the effect of externality cost on the PW footprint for different PW management pathways. Inspired and modified by Klemeš et al. (2021), PW footprint is defined as the sum of the budget and externality cost of a particular PW management pathway, as shown in Eq(1). Two scenarios are proposed in this study: (1) PW management with externality consideration and (2) PW management without externality consideration (i.e., baseline scenario). The PW footprint resulting from each scenario is compared and analyzed.

$$\text{Plastic waste footprint} = \sum Ext_n + Rev_n - CAPEX_n - OPEX_n \quad (1)$$

Where Ext_n denotes the externality cost, Rev_n represents the revenue gained from the secondary product sales, $CAPEX_n$ and $OPEX_n$ the capital and operating expenditures in the n stages within the system boundary, n is the selected pathway for PW management system (i.e., landfilling, incineration, mechanical recycling).
To investigate the influence of externality cost towards the BCR calculation in conventional economy systems, life-cycle BCR is introduced as Eq(2) to consider externality cost as one of the important cost components. The quantitative comparison between the conventional BCR (excluding externality cost) and life-cycle BCR for different PW management pathways is also carried out.

$$\text{Life-cycle benefit-cost ratio} = \frac{\textit{Net profit}_n}{\textit{Expenditure}_n} \quad (2)$$

Where represents the *Net profit*$_n$ sum of revenue and externality gain in n pathway, *Expenditure*$_n$ denotes as the sum of $CAPEX_n$, $OPEX_n$, and externality loss.

3. Results and Discussion

Figure 2 illustrates the individual endpoint assessment of the landfill, mechanical recycling, and incineration pathways. The mechanical recycling pathway appears as the most environmentally-favoured pathway, contributing up to 62 % of environmental savings compared to the other pathways. The incineration pathway (i.e., inclusive of PW transportation) shows an inconsistent trend across the three categories of endpoint assessment, generating 8 % and 34 % environmental burdens in human health and ecosystem quality categories while inducing 10 % environmental saving in resource scarcity. The findings of this study reveal waste transportation is a major hotspot in the landfill pathway, exerting approximately 96 % damage in resource scarcity over the entire life cycle (Figure 2(c)). This is due to the long distance between the PW collection sites and the landfills (landfills are required to be sited further compared to other PW management facilities (DOE, 2012)). Location optimization between the PW collection sites and PW management facilities is prospective to reduce this process's economic and environmental burden (Ooi and Woon, 2021).

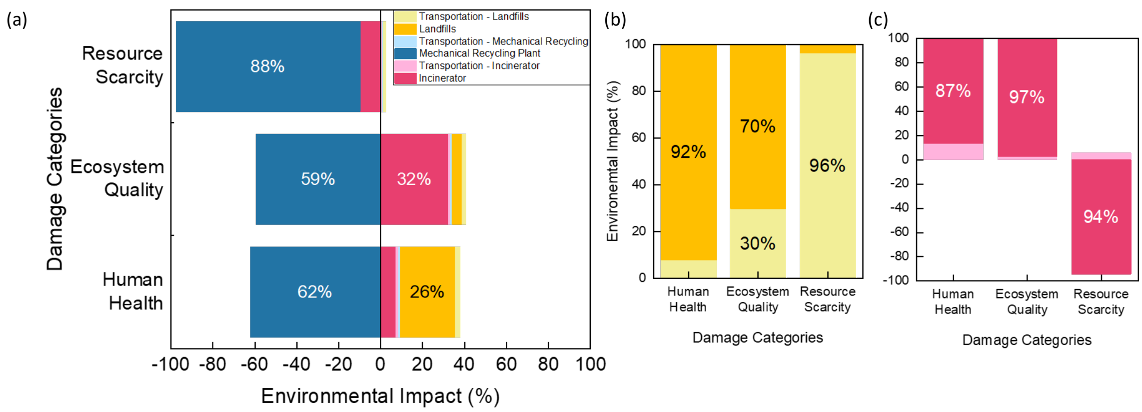

Figure 2: (a) Overall life cycle environmental assessment for landfilling, incineration, and mechanical recycling pathways. Environmental impact breakdown of (b) landfill and (c) mechanical recycling pathways.

A comparative assessment between the scenarios with and without the externality cost consideration in the LCC of PW management pathways is conducted (Figure 3). The externality cost in the PW footprint is directly proportional to the environmental performance of different PW treatment pathways. A negative 5.4 times difference in PW footprint is observed in the incineration pathway when externality cost is included due to the terrestrial ecotoxicity triggered by vanadium emission from the waste facility (Woon and Lo, 2016). Mechanical recycling and landfilling pathways show a 1.9 % and 56 % PW footprint difference. The mechanical recycling pathway has a positive PW footprint (i.e., 412.70 US$$_{2022}$ t^{-1} PW), while landfilling pathway has a negative PW footprint (i.e., 53.38 US$$_{2022}$ t^{-1} PW) in both scenarios. Unlike other pathways, including externality cost in mechanical recycling has increased the PW footprint, as supported the study outcomes by Andreasi Bassi et al. (2022). The research findings suggest that the PW footprint performance of the investigated PW management with externality consideration is ranked as follow in descending order: Mechanical recycling, landfilling, incineration. Whereas, the performance ranking alters (i.e., incineration precedes over landfilling) when externality cost is excluded, showing that externality cost remarkably affects the PW management sustainability.

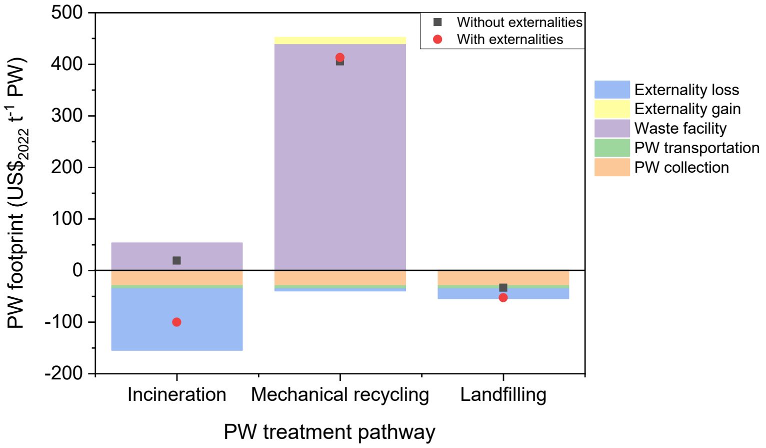

Figure 3: PW footprint comparison for landfilling, incineration, and mechanical recycling pathway

The conventional BCR of the PW management pathways ranges from 0.17-10.9, with the mechanical recycling pathway as the highest due to the lucrative profit from recycled plastics (i.e., 92 % of revenue), while landfilling pathway is the lowest (Table 2). Compared to life-cycle BCR, all PW management pathways face 7-66 % reductions. The incineration pathway succumbs to the sharpest drop to 0.44 because of low FiT income and high externality loss (Chin et al., 2022a). Similarly, the lower life-cycle BCR of landfilling pathway compared to conventional BCR resulted from the same reasons as the incineration pathway. Though considered 14 % of sanitary landfills in landfilling pathway, the negligible impact from FiT fails to diminish the environmental and economic burdens from open landfills. Total expenditure is negatively correlated to life-cycle BCR. PW collection and sortation in different pathways are stages attributed to the largest expenditures in different pathways. PW collection fee is 1.9–116 times greater than other individual cost components in the waste management facilities. Transportation cost for PW is 3 %–61 % greater than the operating costs of mechanical recycling plants and landfills but 77 % less than that of the incineration plant. By cutting expenditures from collection fees and transportation, the life-cycle BCR of respective pathways can be further reduced.

Table 2: Comparison between conventional benefit-cost ratio and life-cycle benefit-cost ratio

PW management pathway	Conventional benefit-cost ratio	Life-cycle benefit-cost ratio
Incineration	1.30	0.44
Mechanical recycling	10.9	10.1
Landfills (including sanitary landfills)	0.17	0.12

4. Conclusions

PW footprint and life-cycle BCR under an integrated LCA-LCC methodology for sustainable PW management have demonstrated the significance of comparing the research outcomes from the conventional economy and green economy facets. PW facilities and transportation are the main environmental hotspots in PW management, where PW facilities generally have a higher environmental load than PW transportation. In terms of environmental and economic performances, the mechanical recycling pathway in PW management consistently appears to be superior to the incineration and landfilling pathways, with the highest PW footprint (i.e., 412.70 $US\$_{2022}$ t^{-1} PW) and life-cycle BCR regardless of the presence of externality cost. The incineration pathway has the lowest PW footprint and a life-cycle BCR <1, which resulted from the high externality cost and low-profit income from secondary product recovery (i.e., FiT from electricity generation). PW footprint and life-cycle BCR are suitable as performance indicators for PW value chain stakeholders in circular PW economy decision-making. Geospatial and waste management pathway optimization are recommended for future studies of this integrated framework to enhance the feasibility of the proposed green PW management indicators.

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