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Policy-driven municipal solid waste management assessment using relative quadrant eco-efficiency: A case study in Malaysia

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ABSTRACT

Despite studies encouraging sustainable waste management, most municipal wastes remain in landfills, particularly in developing countries. Lack of holistic planning and national policy alignment might impair the waste management facility implementation. Policy-driven waste treatment scenarios should be designed to strongly link to the local conditions when assessing the eco-efficiency impacts of the waste management system. Taking Malaysia as a case study, a relative quadrant life cycle eco-efficiency indicator is developed to investigate the eco-efficiency of waste treatment scenarios. The relative quadrant life cycle eco-efficiency indicator depicts the eco-efficiency of various waste management scenarios. Compared with Scenario S1 – business-as-usual (i.e., 71.5% open landfill, 10% sanitary landfill, 1% composting, 17.5% recycling), five waste treatment scenarios (S2–S6) are designed based on Malaysia's existing and future policy targets. Scenario S5 (15.5% sanitary landfill, 22.25% composting, 22.25% anaerobic digestion, 40% recycling) and Scenario S6 (5% sanitary landfill, 22.25% composting, 22.25% anaerobic digestion, 40% recycling, 10.5% incineration) demonstrate that the 40% recycling rate is 32.9–33.6 times more environmentally favorable and 10–20% more economically viable than business-as-usual. Another four scenarios (NS1-NS4) are designed to investigate zero waste in landfills and the need to implement incineration or material recovery. Scenario NS3 suggests increasing incineration capacity to 33% could be an option should incineration is implemented. Adopting home or centralized windrow composting and increasing 2.5–5.5 times of current Feed-in Tariff rates are recommended to improve the eco-efficiency of the waste treatment scenarios. This study could facilitate policymakers to set waste minimization targets and incentives through various scenarios via sensitivity and comparative analyses.

1. Introduction

National policies, targets, and action plans on waste management are enacted to develop an environmentally sustainable and economically viable municipal solid waste (MSW) management system. Examples include landfill disposal bans in the United States (Northeast Recycling Council, 2017), mandatory food diversion for composting (Newsom, 2009), and circular economy adoption of MSW management in Malaysia (KPKT, 2019). The national-level decisions on waste management and treatment are made according to the targets and strategic action plans given under the policy. It is crucial to identify the synergistic effect between waste treatment and disposal's environmental and economic impacts based on national targets and action plans. This aims to establish a strong connection between the outcomes and local conditions and needs.

Life cycle assessment (LCA) on MSW treatment identifies the hotspot activities with significant environmental impacts, while life cycle costing (LCC) analyses the potential market value of the MSW treatment (Lin et al., 2022). A vast amount of research simultaneously evaluates LCA and LCC in MSW management systems, but the results for LCA and LCC are interpreted separately (See Table 1). Wang et al. (2020) found that MSW separation has the greatest burden from an environmental perspective, while the equipment cost has the most significant economic impact. These studies did not integrate the environmental and economic impacts of the waste treatment, for instance, by combining them into an integrated indicator system. The decision-making process is not holistic without an integrated LCA and LCC assessment to evaluate the overall performance. The outcomes would be easily biased to a single impact. An integration study is required to overcome this limitation.

Eco-efficiency investigates the life cycle environmental impacts of the MSW treatment and its economic value by integrating both results,

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Abbreviation

12 MP	12th Malaysia Plan
AD	Anaerobic digestion
BAU	Business-as-usual
BCR	Benefit-cost ratio
Comp	Composting
COP26	26th United Nations Climate Change Conference
DALY	Disability Adjusted Life Year
FiT	Feed-in Tariff
FU	Functional unit
GHG	Greenhouse gas
Icn	Incineration
IntF	Integrated facility
LCA	Life cycle assessment
LCC	Life cycle costing
LFG	Landfill gas
MRF	Material recycling facility
MSW	Municipal solid waste
OL	Open landfill
Rcy	Recycling
SDG	Sustainable development goal
SL	Sanitary landfill
TWtE	Thermal waste-to-energy
ZOL	Zero landfill gas

according to ISO 14045:2012. Understanding the synergetic relationship between environmental and economic impacts is essential as the world strives for economic progress without comprising the environmental status. Eco-efficiency analysis on MSW management is relatively limited compared to the independent environmental and economic assessment. Woon and Lo (2016) and other works of literature (See Table 1) conducted an eco-efficiency assessment that integrated the environmental and economic life cycle performance of individual waste facilities. It is difficult to extrapolate the results of these studies to the actual waste treatment situation. Unless all the MSW is dumped at the disposal site, MSW is usually separated and treated in different treatment facilities due to its heterogeneity.

Table 1 shows that some studies, such as Ibáñez-Forés et al. (2021), evaluated the waste treatment in various combinations of waste treatment scenarios. The treatment combinations have not been designed according to the existing national policy's target. The outcomes might not be practical for improving the existing MSW treatment conditions. The planned treatments may not be feasible as the allocated governmental incentive has not been evaluated for their eco-efficiency level. Designing studied waste treatment scenarios with policy-driven support is recommended to cater to the study's feasibility and practicability. Policy-driven scenario analysis could facilitate the benchmarking level of the incentive provisions for some transitions. Paes et al. (2020a, 2020b) assessed the eco-efficiency performance of waste treatment combinations in Brazil based on the National Solid Waste Management Plan's landfill reduction target. The eco-efficiency results for each scenario are presented in an "environmental vs cost" diagram. This diagram merely illustrates the result subject to the exact environmental and economic impact value at a certain point. The degree of eco-efficiency for various scenarios remains uncertain.

This study investigates the eco-efficiency of the policy-driven scenarios with different waste treatment combinations based on the national targets and action plans. A relative quadrant eco-efficiency indicator system is developed to integrate each scenario's life cycle environmental and economic impacts. This graphical indicator keeps the two-dimensional information and can demonstrate the adjustment of the two indicators based on the option's location (Ng et al., 2015). The relative quadrant eco-efficiency indicator is constructed in four quadrants to provide an intuitive and illustrative expression of the eco-efficiency performance in terms of LCC vs LCA. The results shown compares the eco-efficiency performance of policy-driven MSW treatment scenarios to the business-as-usual (BAU) practice of the MSW treatment. Sensitivity analysis is conducted to evaluate whether the results' robustness is affected by critical parameters via the scenarios' repositioning in the indicator. Alternative treatment combinations are also designed based on the common waste treatment practice and targets from other regions for further investigation in scenario analysis.

Based on the findings, this study provides policy recommendations for national MSW policy-driven targets. These recommendations are significant for policymakers and local authorities to further improve solid waste treatment policies. Action plans are suggested to achieve or revamp the existing MSW targets. Nations with comparable solid waste management or regional conditions may refer to the proposed policy implications and recommendations to improve their current situation. This study also hopes to contribute to the knowledge of eco-efficiency assessment by developing and applying the relative quadrant eco-efficiency indicator to evaluate the eco-efficiency performance of the solid waste treatment system with the integration of environmental and economic impact.

2. Methodology

Fig. 1 shows the overall framework of this study. The study has five main phases: 1) geographical boundary and scope definition, 2) MSW treatment scenarios, 3) environmental and economic analysis, 4) eco-efficiency assessment, and 5) policy implication. The details of each phase are elucidated in the following sub-section (Section 2.1-2.6).

2.1. Phase 1: geographical boundary and scope definition

Malaysia, with a population size of 32.7 M in 2021 (annual growth rate of 0.2%) (Mahidin, 2021) and an average waste generation rate of 1.17 kg/ca/d (MESTECC, 2018), is selected for the study. The national waste composition mix in Malaysia is shown in Table B1 (Appendix B), where the highest portion comprises food waste (44.5%). The MSWs include the solid waste generated from households, industrial, commercial, and institutions.

2.2. Phase 2: MSW treatment scenarios

With the rapid increase in MSW generation, the Malaysian government has introduced policies and action plans to treat the MSW environmentally friendlier manner. These include Action Plan for a Beautiful and Clean Malaysia 1987, National Solid Waste Management Policy 2006 (revised in 2016), and National Cleanliness Policy 2020. A few targets are proposed in Malaysia's policy reports, for instance, 40% of the recycling rate by 2025 under the 12th Malaysia Plan (12 MP) 2021–2025, 80% of sanitary landfills (SL) by 2030 under the Green Technology Master Plan 2017–2030, and 95% of integrated facilities under 12th Malaysia Plan 2021–2025.

In line with Malaysia's policy reports and targets, six scenarios (S1 to S6) are designed for assessment. The detailed waste treatment and disposal diversion for each scenario are summarized in Table 2, while their calculation is provided in Section B1.4 (Appendix B).

Scenario 1 (S1) is the BAU case where the MSW is treated by open landfill (71.5%), sanitary landfill (10%), composting (1%), and recycling (17.5%) (Kaza et al., 2018). Scenario 2 (S2) assumes that 80% of waste is diverted from open landfills (OLs) to SLs, as captioned in the

Table 1
Literature study of environmental and economic studies on different solid waste treatment scenarios.

Reference	Assessment[a]			Eco-efficiency indicator/approach	Scenario for treatment facility[b]	Policy-based scenario[c]	Study objective
	Env.	Econ.	E/E				
Torkashvand et al. (2021)	x	/	x	–	Individual	–	To determine the cost-benefit of different plastic solid waste routes with a proposed economic model
Wang et al. (2022)	/	X	x	–	Combination	/	To investigate the transition of local MSW management practice after implementing the EU directives and the GHG emissions reduction
Fei et al. (2018)	/	/	x	–	Individual	–	To compare the energy, environmental, and economic impacts of mechanical-biological treatment (MBT) systems before and after being integrated into landfill and incineration
Ayodele et al. (2018)	/	/	x	–	Individual	–	To evaluate the economic benefits, environmental, and energy savings of recyclables
Singh and Basak (2018)	/	/	x	–	Individual	–	To compare various MSW treatment techniques for dry and wet wastes in environmental and economic terms
de Feo et al. (2019)	/	/	x	–	Individual	–	To evaluate the environmental and economic performance of material recovery in MSW system
Chen et al. (2019)	/	/	x	–	Individual	–	To compare the environmental, economic, and energy impacts of incineration in different scenarios
Lim et al. (2019)	/	/	x	–	Individual	–	To evaluate the GHG emissions and the cost-benefits analysis of a community-composting site
Keng et al. (2020)	/	/	x	–	Individual	–	To explore the feasibility of diversifying the food waste to community-scale open-pile composting
Wang et al. (2020)	/	/	x	–	Combination	X	To explore the environmental and economic performance of an integrated MSW treatment plant
Mayer et al. (2020)	/	/	x	–	Combination	x	To determine the preferable organic waste treatment pathway from the economic and environmental points of view
Sun et al. (2021)	/	/	x	–	Individual	–	To compare the techno-environmental-economic performance of waste-to-power/fuel technologies by gasification- and incineration-based routes
Woon and Lo (2016)	/	/	/	Modified eco-efficiency indicator	Individual	–	To evaluate the eco-efficiency of proposed landfill extension and advanced incineration facility using the modified eco-efficiency indicator
Mah et al. (2018)	/	/	/	Environmental-cost effectiveness diagram	Individual	–	To identify the most environmental- and cost-efficient waste management method for concrete waste
Slorach et al. (2019)	/	/	/	Average ranking score	Individual	–	To identify the most environmentally and economically sustainable treatment option for food waste in the context of a circular economy
Lu et al. (2020)	/	/	/	Weighted sum of normalized impact	Individual	–	To compare the environmental and economic performance of composting at the household and community scale
Yi and Lim (2021)	/	/	/	Single score	Individual	–	To assess the eco-efficiency of waste treatment facilities under various operating conditions
Zheng et al. (2022)	/	/	/	Integrated hybrid life cycle assessment	Individual	–	To compare the environmental and economic feasibility of MSW incineration fly ash low-temperature utilization in various scenarios by IHLCA
Zhao et al. (2011)	/	/	/	"Global warming vs Cost" diagram	Combination	x	To analyze the eco-efficiency of MSW management in terms of GHG emission mitigation with the proposed methodology
Rigamonti et al. (2016)	/	/	/	"Cost vs Energy & material recovery" diagram	Combination	x	To define an indicator for environmental and economic sustainability assessment of the integrated MSW management systems
Prateep Na Talang and Sirivithayapakorn (2021)	/	/	/	Life cycle cost assessment	Combination	x	To investigate the cost-effectiveness of various MSW disposal schemes for different income groups by incorporating the environmental cost and financial cost
Ibáñez-Forés et al. (2021)	/	/	/	"Environment vs Cost" diagram	Combination	x	To analyze the eco-efficiency of proposed treatment options that could achieve the MSW goals
Abdeljaber et al. (2022)	/	/	/	Eco-efficiency index	Combination	x	To determine the techno-economic and environmental performance of integrated solid waste management strategies based on four waste-to-energy technologies
Paes et al. (2020b)	/	/	/	"Environment vs Cost" diagram	Combination	/	To determine the best eco-efficiency transition pathway among various GHG emission mitigation scenarios in MSW management system
Paes et al. (2020a)	/	/	/	"Environment vs Cost" diagram	Combination	/	To develop an indicator for environmental and economic integration analysis on MSW management system
This study	/	/	/	Relative quadrant eco-efficiency indicator	Combination	/	To investigate the eco-efficiency of policy-driven MSW treatment scenarios and provide policy recommendations

Note: "/" denotes present, "x" denotes unavailable, while "-" indicates not applicable.

[a] The abbreviation "Env.", "Econ.", and "E/E" under assessment refer to environmental assessment, economic assessment, and eco-efficiency assessment, respectively. Eco-efficiency assessment integrates environmental and economic results, exploring the environmental impact and its monetary value. Literature without eco-efficiency indicates that a study interprets the environmental and economic impacts separately.

[b] Individual indicates that the scenario assessed is the individual treatment facility where all the waste generated is assumed to treat in one facility; combination indicates that the scenario assessed is in treatment combination, where the waste generated is diverted into various treatment facilities.

[c] Policy-based scenario is defined when the scenario for assessment is created based on the government's targets, policies, or directives.

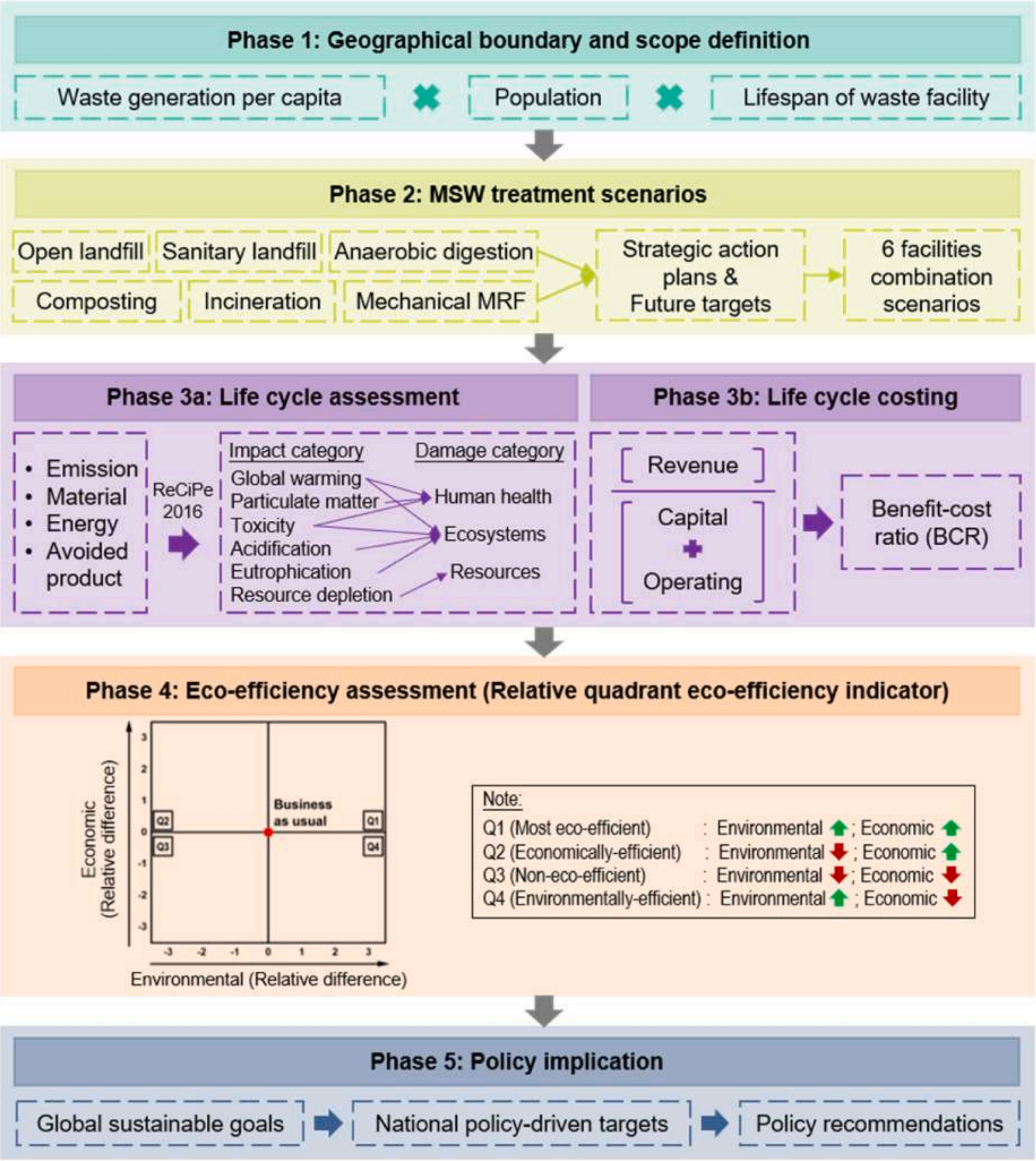

Fig. 1. The overall framework of the study.

Table 2
Summary of study waste treatment scenarios.

Scenario	Waste treatment and disposal (%)						Relevant policy-driven target[a]
	Open landfill	Sanitary landfill	Composting	Anaerobic digestion	Incineration	Material recovery	
S1 (BAU)	71.5	10	1	–	–	17.5	A
S2 (80% SL)	1.5	80	1	–	–	17.5	B
S3 (3 TWtE)	63.8	10	1	–	7.7	17.5	C
S4 (ZOL)	–	38	22.25	22.25	–	17.5	D, E
S5 (40% Rcy)	–	15.5	22.25	22.25	–	40	D, E, F
S6 (95% IntF)	–	5	22.25	22.25	10.5	40	D, E, F, G

Note.

[a] A: Business-as-usual (Kaza et al., 2018); B: 80% sanitary landfill under Green Technology Master Plan Malaysia 2017–2030 (KeTTHA, 2017); C: 3 WtE thermal plants under Green Technology Master Plan Malaysia 2017–2030 (KeTTHA, 2017); D: zero open landfill (Azman, 2020); E: zero-food waste to landfill (Sri Priya, 2020); F: 40% recycling rate in 12 MP 2021–2025 (Economic Planning Unit, 2021); G: 95% integrated facilities, 5% sanitary landfill in 12 MP 2021–2025 (Economic Planning Unit, 2021).

Green Technology Master Plan Malaysia 2017–2030, while the other waste treatment fraction remains the same. Scenario 3 (S3) is formulated according to another target in the Green Technology Master Plan Malaysia 2017–2030; a portion of OL waste is diverted to three waste-to-energy (TWtE) thermal plants (i.e., incineration) with 1000 t/d of capacity. Scenario 4 (S4) is designed based on zero open landfill and zero-food waste in landfills targets. All food waste is treated with composting and anaerobic digestion, and the recycling rate remains unchanged, while other wastes are disposed of in SLs. Scenario 5 (S5) sets a 40% recycling rate on top of S4. Scenario 6 (S6) considers that 95% of waste is treated in integrated facilities, and 5% is disposed of in SLs while maintaining a 40% recycling rate.

2.3. Phase 3a: life cycle assessment

In line with ISO 14040:2006 and ISO 14044:2006, this phase evaluates and compares the environmental impact incurred by the treatment facilities in various studied scenarios over 30 y (from 2016 to 2045). The system boundary for this assessment involves the operational process from the waste disposed to the treatment site to the substitution process of the recovery products (electricity, fertilizer, and recycled plastic pellets). The overall process flow of the system boundary can be found in Figure B1 in Appendix B.

Foreground data for each treatment facility, such as material and energy consumption, air and water emissions, and recovery product yield, are sourced and calculated from the National Solid Waste Management Department's reports and peer-reviewed journal articles. The raw data for foreground inventory and their references can be found in Appendix A. After referring to the functional unit (FU) (1 t of MSW on a wet basis), the life cycle inventory is tabulated in Table B3 (Appendix B). Background data (e.g., air emissions from diesel production) are attained from the Ecoinvent v3.8 database. The life cycle impacts for the six scenarios are assessed using SimaPro 9.3 software with ReCiPe 2016. ReCiPe 2016 has been widely adopted due to its relatively low results' uncertainty (Mulya et al., 2022). The midpoint impact categories measure the common reference emission or extraction, and the endpoint damage categories are the reflection points of the impact categories, showing the potential outcomes. This study includes global warming, fine particulate matter formation, human carcinogenic toxicity, human non-carcinogenic toxicity, terrestrial acidification, freshwater eutrophication, marine ecotoxicity, and fossil resource scarcity as midpoint categories, while human health, ecosystem, and resources as endpoint damage categories. The characterization factor equations for each impact category and the midpoint-to-endpoint calculation are provided in Section B3.2 (Appendix B).

2.4. Phase 3b: economic analysis

With the same scope and boundary described in Section 2.3, each facility's costing data is obtained from the National Solid Waste Management Department's report and peer-reviewed journal articles (cited in Appendix A). The data referred to FU is presented in Table B4 (Appendix B). The costing data considered in this study are the capital cost, operating cost, and income from the recovery products. The capital cost is annualized with Eq. (1), assuming that the costs are discounted to 2021 with a 4% discount rate and a 30-y operating period.

$$EAC = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \quad (1)$$

EAC = Equivalent annual cost (MYR/y), P = Present value or capital cost (MYR), I = discount rate (%), n = lifespan of waste treatment facility (y).

Feed-in Tariff (FiT) for bioelectricity substitution is considered to identify the economic impact before and after introducing the incentive. The data inventories are converted to a similar functional unit and tabulated in Table B4 (Appendix B). The cost impact is analyzed by the benefit-cost ratio (BCR) indicated in Eq. (2). The studied scenario delivers a positive net present value if the BCR value obtained is greater than 1.0.

$$Benefit - cost\ ratio\ (BCR) = \sum(CC_i + OC_i) \Big/ \sum In_i \quad (2)$$

CC = capital cost of the waste treatment facility (MYR), OC = operating cost expenses during the waste treatment process (MYR), In = income gained from the recovery products (MYR), i = waste treatment facility.

2.5. Phase 4: eco-efficiency assessment

According to ISO 14045:2012, eco-efficiency is a tool that investigates the synergetic relationship between the life cycle environmental assessment of a product system and its product value (i.e., monetary). It aims to reconcile ecology and economic development. The individual results from the environmental (single score) and economic (BCR) analysis in Phase 3a and 3b are integrated into a relative quadrant indicator (See in Fig. 1). This indicator eases the eco-efficiency interpretation of a waste treatment scenario in a visualization form. The results are compared to the BAU case in which the value obtained is the relative difference between the five scenarios and BAU, which can be calculated as Eq (3).

$$Relative\ difference_{env/econ} = \frac{E_{scenario} - E_{BAU}}{E_{BAU}} \quad (3)$$

E = single score from environmental (env) or BCR from economic (econ) assessment, $scenario$ = various studied scenarios except for Scenario 1 (BAU), BAU = the reference scenario, i.e., Scenario 1 (BAU).

The results can be interpreted in four quadrants (Q1, Q2, Q3, and Q4), as shown in Fig. 1. The description of the scenario's performance falls under the four quadrants is given below.

i. Q1 (most eco-efficient): higher environmental and economic benefits than BAU
ii. Q2 (economically-efficient): higher economic benefits but lower environmental performance than BAU
iii. Q3 (non-eco-efficient): lower performance in both environmental and economic aspects than BAU
iv. Q4 (environmentally-efficient): higher environmental but lower economic performance than BAU

Technical parameters, including landfill gas (LFG) conversion rate (20–80%) and energy recovery efficiency at incineration plants (30–80%), are considered in the sensitivity analysis to check the robustness and the breakout point towards the higher eco-efficient quadrant. These parameters were chosen as the current efficiency for both technology is low and can be increased since the enhanced technology is available. The FiT rate for electricity generation (2–6 times) is analyzed to determine the desired increment for each scenario to have higher cost-effectiveness than BAU for current technology. More waste treatment scenarios with different combinations (Table B6 in Appendix B) and the implementation of subsidy to compost (10–100%) are conducted in the scenario analysis to identify the need for better waste treatment transformation. The new scenarios are formulated by referring to the waste treatment distribution from other countries (e.g., Japan, Netherlands) with the questions below.

1) Is zero-food waste to landfill a "must-implemented" target?
2) What is better for waste treatment, material recovery, or incineration?
3) Is it ideal to treat most of the waste by incineration?

2.6. Phase 5: policy implication

National solid waste management and relevant policies (e.g., 12 MP, 2021–2025, Green Technology Master Plan, 2017–2030, Malaysia Renewable Energy Roadmap, 2022–2035) are discussed based on the global sustainable goals such as the Paris Agreement, United Nations Sustainability Development Goals (SDGs), and 26th United Nations Climate Change Conference (COP26). The recommendations for waste policymaking and targets are provided from the eco-efficiency results. The discussion proposes the recycling rate target, composting method, renewable electricity generation from waste facilities, and FiT for electricity generation from LFG and waste biomass, taking Malaysia as a case study.

3. Results and discussion

3.1. Life cycle interpretation on environmental impacts

The environmental impact results for each scenario in endpoint damage categories are illustrated in Fig. 2, while the midpoint impact categories' results and discussion can be found in Figure B3 and Section B3.4 (Appendix B). The combination of scenarios benefits the environment when the results are negative, while the positive value results indicate the adverse impact.

The overall environmental performance of the six scenarios is ranked by: S1 (BAU) < S3 (3 TWtE) < S2 (80% SL) < S4 (ZOL) < S5 (40% Rcy) < S6 (95% IntF), in human health and ecosystems. S1 (BAU) and S3 (3 TWtE) incur a net environmental burden on human health (S1 – 1.4 × 10^{-4} DALY/t MSW; S3 – 1.96 × 10^{-5} DALY/t MSW) and ecosystems (S1 – 6.42 × 10^{-7} species.y/t MSW; S3 – 3.24 × 10^{-7} species.y/t MSW), where global warming accounts for the highest allocation (51–63%). More than 60% of total MSW is dumped in OL, producing high GHG emissions, such as methane into the atmosphere. Similar findings were obtained by Vinitskaia et al. (2021) and Wang et al. (2022) regarding the inability of the avoided impact contributed by recycling to outweigh the adverse impact caused by landfills in the global warming when the amount of MSW disposed of in landfills is higher than recycling.

Among the designed scenarios, S5 (40% Rcy) and S6 (95% IntF) perform the best in all endpoint damage categories. This is due to the avoided impact of the mechanical material recovery facility (MRF). MRF shows the most promising waste treatment method as it dominates the avoided impact for all damage categories across various scenarios. Results reveal that improving the recycling rate by 22.5% (i.e., from the current 17.5%–40%) could improve the environmental performance by four-fold in human health, 4.4 times in ecosystems, and 1.8 times in resources. Paes et al. (2020b) supported this finding, emphasizing the importance of maximizing the recycling rate for dry waste. Treating waste in the MRF is unlikely to emit harmful gaseous during the treatment process. In contrast, the ground recyclables could transform into new products, indirectly avoiding the environmental impact of virgin material production.

S4 (ZOL) has the lowest net environmental performance of all treatment scenarios without OL disposal (−5.93 × 10^{-4} DALY/t MSW in human health, −1.62 × 10^{-6} species.y/t MSW in ecosystems, −60.68 USD2013/t MSW in resources). In S4 (ZOL), all food waste is treated appropriately under aerobic (i.e., tunnel composting) and anaerobic (i.e., anaerobic digestion) conditions. Although gaseous and liquid emitted from the organic matter decomposition process are controlled, tunnel composting results in adverse net environmental impacts on human health and ecosystems. The environmental burden of composting presence in each midpoint impact category was due to the high energy consumption that incurs adverse environmental impacts and low compost yield. The avoided impacts for each impact category from compost are insignificant to outweigh the overall environmental load incurred by the tunnel composting. Lu et al. (2020) showed that household or centralized open-windrow composting could double the environmental benefits. Their energy consumption is lesser than the centralized in-vessel composting (tunnel composting).

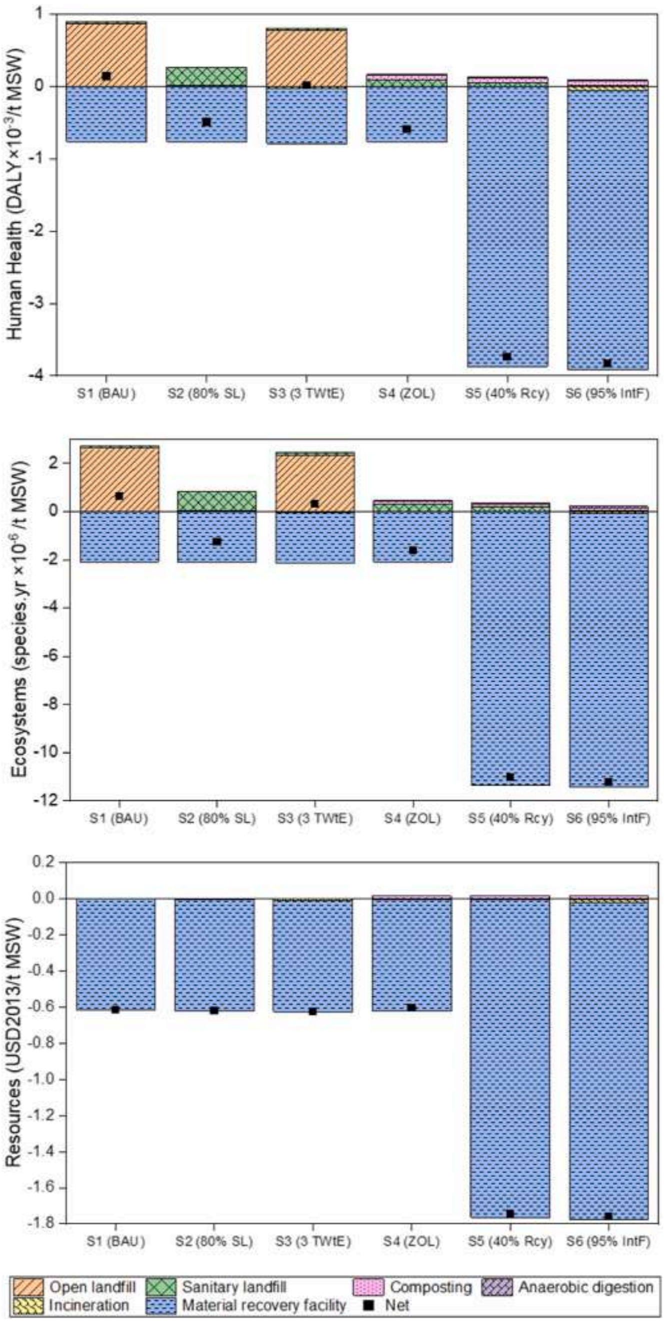

Fig. 2. Damage assessment results for studied scenarios in human health, ecosystems, and resources (FU: 1 t of MSW). The positive value indicates the adverse environmental impact incurred by the treatment facility, while the negative value represents the environmental benefit.

3.2. Benefit-cost ratio (BCR) analysis

Table 3 presents the BCR analysis results for the studied scenario. The result value for all the scenarios is greater than 1.0 except for S4 (ZOL). This implies that all other scenarios are profitable except for S4 (ZOL). According to the calculation (Table B4 in Appendix B), S4 (ZOL) has a low BCR value owing to the low compost yield. Consequently, the income from compost is relatively low (0.1 MYR/t MSW) compared to the capital (4.6 MYR/t MSW) and operating costs (16.6 MYR/t MSW) of tunnel composting. Other recovery products from other treatment

Table 3
Benefit-cost ratio (BCR) results of the studied scenarios with and without implementing FiT.

Scenario	BCR (without FiT)	BCR (with FiT)	Variation (%)
S1 (BAU)	1.2339	1.2371	0.26
S2 (80% SL)	1.0100	1.0303	2.01
S3 (3 TWtE)	1.0950	1.1285	3.06
S4 (ZOL)	0.8461	0.8818	4.22
S5 (40% Rcy)	1.4775	1.5058	1.92
S6 (95% IntF)	1.3533	1.4035	3.71

facilities do not generate enough revenue to compensate for the cost gap caused by composting. BCR value for S5 (40% Rcy) and S6 (95% IntF) is higher than S1 (BAU) mainly due to the increasing recycling rate, which generates considerable revenue from the recyclables. Compared to S5 (40% Rcy), waste treatment with incineration has a high capital cost, leading S6 (95% IntF) to a lower BCR value (8.4% lower).

The BCR value of S3 (3 TWtE) is affected by the high capital cost of incineration, resulting in an 11.2% lower BCR value than S1 (BAU). The BCR value for S2 (80% SL) is 18.1% lower than S1 (BAU) due to the high operating cost of SLs. Table 3 shows that implementing FiT increases the BCR value for each scenario. The increment of BCR value for various scenarios after considering FiT is insignificant (i.e., 0.26–4.22%, depending on the treatment percentage of the waste facility). The reason is that the electricity generation efficiency from each scenario is low. Technology improvements, such as the landfill gas conversion rate and electricity generation efficiency, are crucial to overcoming this issue at the current FiT rate and contributing to greater renewable energy.

3.3. *Relative eco-efficiency*

The eco-efficiency results of various scenarios are illustrated in Fig. 3. The results are all presented relative to the S1 (BAU) case. The negative value indicates that the performance in the particular aspect is inferior to the BAU case, while the positive value indicates the opposite. Q1 (most eco-efficient) indicates the region's scenario has a higher environmental and economic impact than the BAU; Q2 (economically-efficient) indicates the region's scenario has a greater economic but lower environmental impact than the BAU; Q3 (non-eco-efficient) indicates the region's scenario has a lower environmental and economic impact than the BAU; Q4 (environmentally-efficient) indicates the region's scenario has a higher environmental but lower economic impact than the BAU. S5 (40% Rcy) and S6 (95% IntF) are located in the Q1 quadrant, indicating that both scenarios' environmental and economic performance is better than BAU. Both scenarios have a high recycling rate (i.e., 40%), implying that recycling benefits both environmental and economic aspects. S5 (40%) is approximately 10% more economically efficient than S6 (95% IntF), while S6 is roughly 2% more environmentally friendly than S5. S2 (80% SL), S3 (3 TWtE), and S4 (ZOL) are situated in Q4; these three scenarios contribute a greater beneficial impact on the environment than the BAU case but a lower economic efficiency. The quadrant location for the three scenarios remains unchanged even when FiT is considered. Improving the recycling rate shall be the prior action to develop a better eco-efficiency for the MSW treatment.

3.3.1. *Sensitivity analysis – conversion of landfill gas to electricity*

Treated landfill gas (LFG) is the main element used to generate electricity from the SL. The current LFG conversion is low, where approximately 3% of LFG collected is converted to electricity while the remaining 97% of LFG is flared. Fig. 4 demonstrates the eco-efficiency results for each scenario after altering the LFG conversion rate. When the conversion rate improves to 30%, S2 (80% SL) increases sharply and shifts from Q4 to Q1. Yet, its environmental efficiency does not surpass S5 (40% Rcy) and S6 (95% IntF). There is only a slight improvement in the eco-efficiency performance for S6 (95% IntF) since only 5% of MSW are treated in SLs. The amount of LFG generated is limited in this instance. The overall eco-efficiency performance of S5 (40% Rcy) goes beyond S6 (95% IntF) when 20% of LFG is converted to electricity. The detailed sensitivity analysis results for energy recovery efficiency at the incineration plants and FiT rate adjustment can be found in Sections B4.3-B4.4 (Appendix B).

3.3.2. *Scenario analysis – alternative waste treatment scenarios*

Based on the results of scenarios located in the most eco-efficient quadrant (S5 and S6), the three listed questions in Section 2.5, and the references from other countries such as Japan, a range of eco-efficiency results of alternative scenarios (NS1, NS2, NS3, and NS4) of MSW treatment has been designed as shown in Fig. 5. NS1 is the most eco-efficient scenario among the four scenarios and is situated in Q1, while NS2, NS3, and NS4 are located in Q4. The results show again that mechanical recycling is the most eco-efficient MSW treatment method. Comparing the eco-efficiency performance of NS1 with NS2 and S6 (95% IntF) with NS3, diverting MSW from recycling to incineration

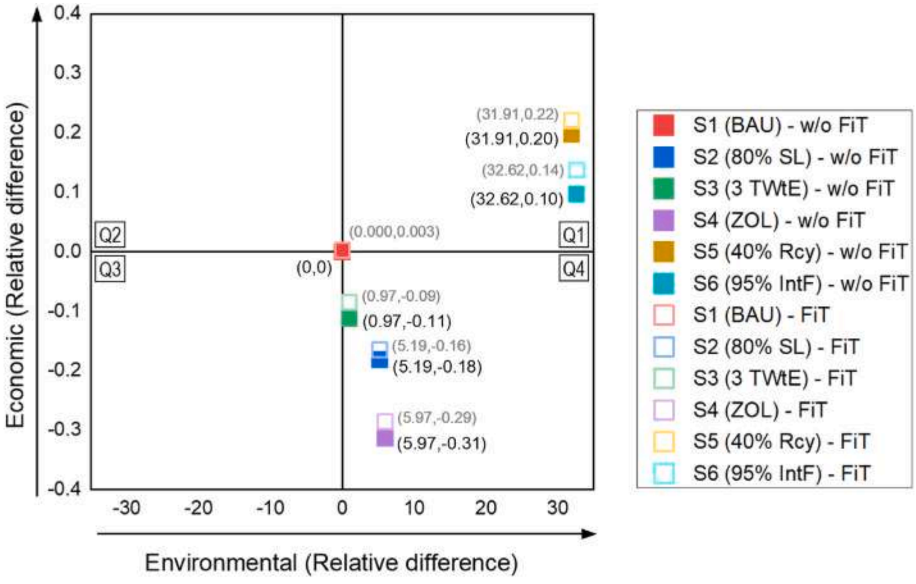

Fig. 3. Relative eco-efficiency of the studied scenarios, with and without Feed-in Tariff (FiT).

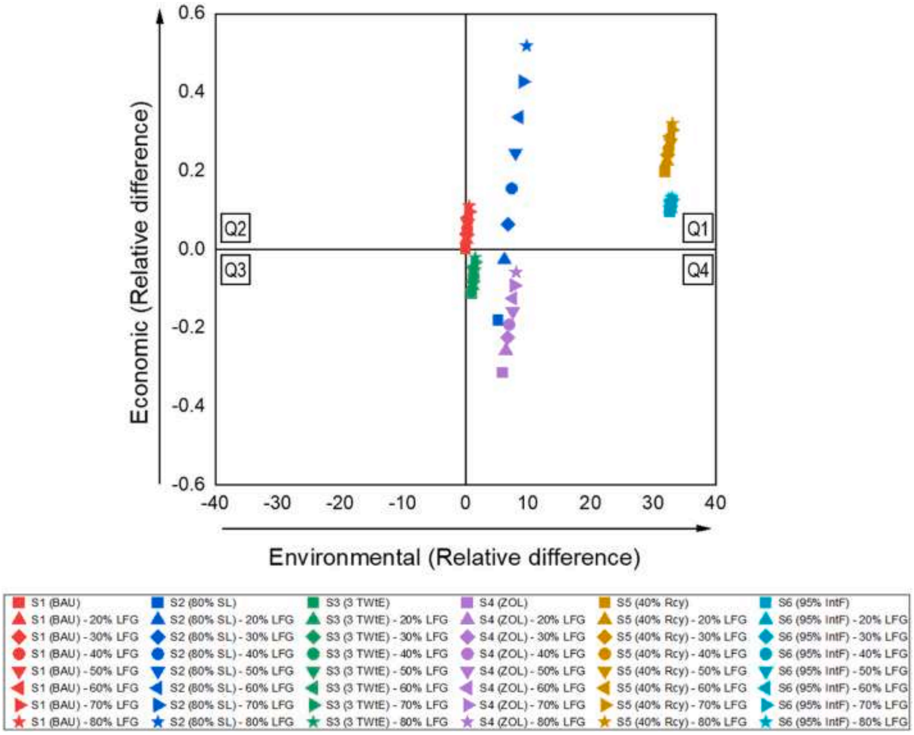

Fig. 4. Sensitivity analysis results for landfill gas conversion.

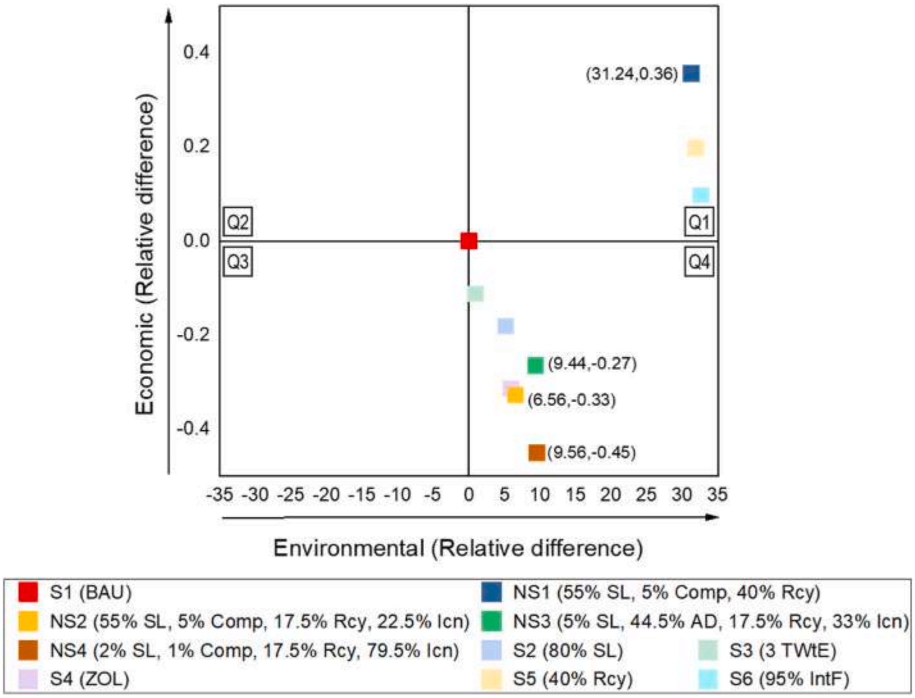

Fig. 5. Scenario analysis results for various waste treatment combination.

neither suggests better environmental nor economic efficiency. NS1 has an even higher economic efficiency than S5 (40% Rcy) and S6 (95% IntF) as NS1 treated more MSW with a higher degradable organic carbon since food waste is treated together. Consequently, the amount of methane generated increases, resulting in higher electricity generation from SLs. The target of zero-food waste in landfills might not be necessary. Food waste can be treated in SLs to produce electricity from LFG, reducing the environmental impacts of grid electricity. Recycling must be performed simultaneously on a massive scale, as the avoided environmental impacts and the waste treatment income are dominantly from MRF.

NS4 possesses the lowest economic efficiency since more than three-quarters of the waste is treated in incineration, thus having a higher expenditure cost. NS2 and NS3 also do not show an outstanding performance in terms of environmental aspects. The treated MSW has a high moisture content, which lowers the burning and energy generating efficiency. It can be concluded that burning all waste in incineration is not an eco-efficient method to treat MSW. The detailed scenario analysis results for implementing subsidies for compost can be found in Section B4.5 (Appendix B).

4. Implications of waste management policies in Malaysia

Solid waste disposal emits high GHG, particularly methane, which hinders the goal of the Paris Agreement. The waste sector is strongly related to eight SDGs (Fig. 6) and can be achieved through efficient waste management. COP26 pledged to reduce methane emissions by 30% compared to 2020, but the waste and resource management industry is excluded in the final agreements. Efforts should be made on top of the actions at COP26 and move towards a circular economy. According to Haigh et al. (2021), implementing a circular economy could slash 39% of global GHG emissions by 2032.

National Solid Waste Management Policy 2006 (revised in 2016) aims to establish a sustainable integrated solid waste management system in Malaysia. The policy has instituted a series of action plans on the modern waste management hierarchy, such as introducing the circular economy concept in solid waste management (KPKT, 2016). The policymakers emphasized the importance of recycling as it could deliver a high commitment to the global climate and sustainable goals. The 12th Malaysia Plan (12 MP) emphasized recycling over other waste treatment methods with a 40% recycling rate target by 2025 (Economic Planning Unit, 2021). The recycling rate in 2021 reached 31.67%, and it is envisaged that Malaysia's recycling rate will increase at least 2% every year (Yuen, 2022). The transition towards a circular economy also enhances the recycling mechanism where products are recycled or recovered at their end-of-life stage (Ooi et al., 2021).

The increment in the recycling rate is proven to significantly outweigh the environmental impacts caused by MSW treatment while contributing to the economy, as raised in Section 3. The nations' production and consumption patterns hinder the recycling growth rate. According to the finding in Section B3.4 (Appendix B), 40% of the recycling rate could shrink by approximately 2.74×10^8 t CO_2 eq annually compared to 17.5% of the recycling rate, which could only reduce 2.61×10^7 t CO_2 eq/y. Kaza et al. (2018) revealed that lower-middle-income countries generate 53% of food and green waste on average. The food system is the primary issue that remains to be tackled (Woon et al., 2021).

Waste treatment such as anaerobic digestion, incineration, composting, and SL can mitigate GHG emissions. Besides recycling, the National Solid Waste Management Policy 2006 (revised in 2016) has targeted redirecting solid waste from disposal sites to waste treatment facilities. It expects 18% of the waste from the 40% of diverted solid waste to be treated through waste treatment facilities (KPKT, 2016). The Green Technology Master Plan 2017–2030 envisions improving the amount of waste treated in SLs and the WtE thermal plant (KeTTHA, 2017). The Housing and Local Government Ministry (KPKT) intends to set up six WtE plants by 2025, including biogas and thermal treatment plants (Azman, 2020). The 12 MP presented that Malaysia has anticipated treating 95% of waste through various treatment facilities, and only 5% of waste is disposed of at SLs (Economic Planning Unit, 2021).

The Ministry envisions building at least one WtE incinerator in each state in Malaysia (Aziz, 2021). Undeniably, diverting MSW from disposal site to incineration potentially reduces the adverse environmental impacts. Yet, the eco-efficiency performance of incineration is unsound due to the high capital and operating cost. This impact is particularly when less MSW is treated in the incinerator (Section 3.3). This is likely to happen when the recycling rate increases, indicating a decrease in dry waste treated by other waste facilities. Incineration of a higher volume of organic waste could reduce energy recovery efficiency. Section 3.3.2 reveals that diverting 33% of waste to incineration would be the best eco-efficiency alternative if incineration has to be implemented. The target of having at least one incineration in each state is not practical as the solid waste amount varies widely across different states in Malaysia. Incinerators can be constructed in certain states that generate more solid waste, but proper recycling is preferable for waste treatment.

Composting activities have been growing moderately in Malaysia. The public lacks awareness of food waste segregation at the source (Hashim et al., 2021). The waste collection for segregated food waste is ineffective, blending all the waste after segregation and ending in the landfill. Decentralize home composting or centralized open-windrow composting can resolve the waste collection problem. Despite GHG releases during these composting processes, they are expected to be at least 30% more environmentally friendly waste treatments than tunnel

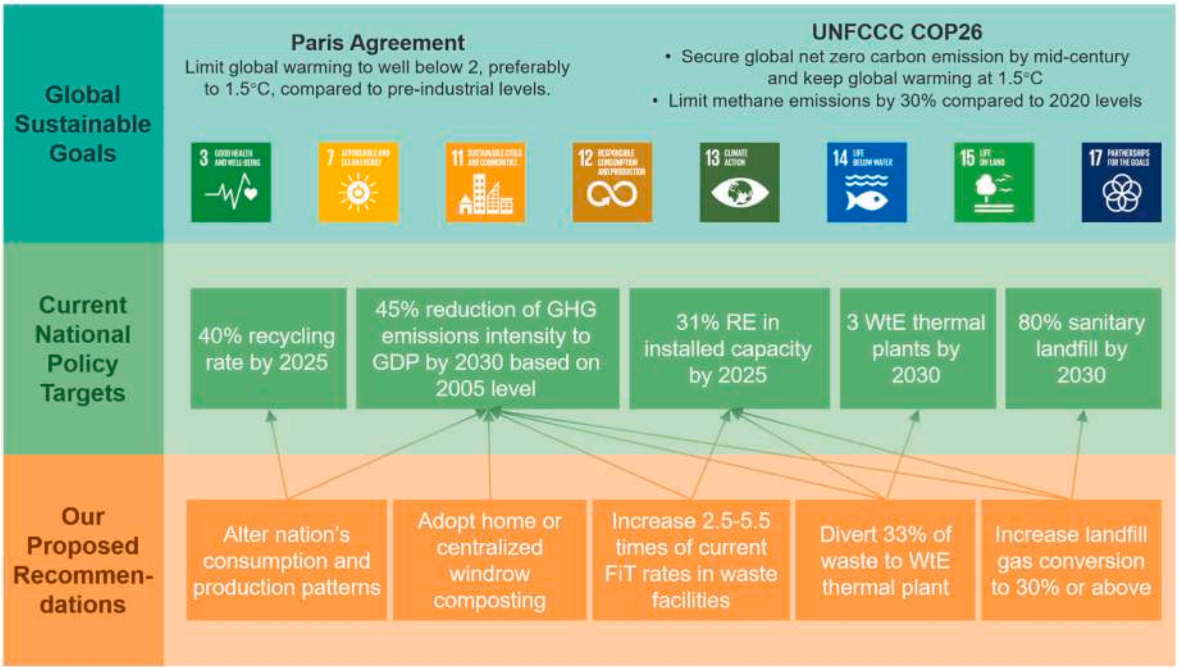

Fig. 6. Policy recommendations for sustainable solid waste management.

composting (Lu et al., 2020). The local authorities can promote capacity building on household composting, provide a composting bin for each household, or prepare a composter in communities. An incentive can be given to quality compost as a reward to arouse participation, e.g., compost buy-back mechanisms by the local authorities for city landscape fertilization.

Sanitary landfill (SL) is the most common treatment method after open landfill (OL), and a target of 80% SL has been established (KeTTHA, 2017). Section 3.3.1 shows that S2 (80% SL) is located in Q4 and shifted to Q1 when the landfill conversion rate increased to 30%. Based on the calculation in Section B4.6 (Appendix B), the current landfill gas conversion rate tends to generate 1.59×10^8 kWh/y of electricity under the 80% SL target, which could mitigate 1.28×10^5 t CO_2 eq of GHG emissions. Increasing the conversion rate to 30% could increase ten times the amount of electricity generated (1.59×10^9 kWh/y), with a 29.7% more benefit-cost ratio gained. It can mitigate 1.15×10^6 t CO_2 eq more GHG emissions yearly than the current SL condition.

The Feed-in Tariff (FiT) incentive could encourage renewable energy production. The current FiT rate for electricity generated from SLs, anaerobic digestion, and incineration does not transform into cost-effective waste treatment facilities (Section B4.4 in Appendix B). The FiT rate should be increased at least 5.5 times (Section B4.4 in Appendix B) to obtain cost-effective results in different waste treatment scenarios. The current cost-effectiveness of the facilities is hindered by technology efficiency; increasing the incentive could prompt the stakeholders to retrofit the electricity generation plant to higher conversion efficiency. This effort aligns with SDG 7 (Affordable and clean energy), encouraging more electricity generated from the waste treatment facility.

5. Conclusion

Eco-efficiency of MSW treatment scenario is essential to be conducted particularly associated with national policies' target to attain the environmental and economic sustainability targets according to the local condition and needs. A relative quadrant life cycle eco-efficiency indicator is developed to investigate the environmental and economic impact relationship for five policy-driven treatment scenarios (S2–S6) relative to the BAU case (S1) from a life cycle perspective. These scenarios combine various waste treatment facilities designed according to the national solid waste management targets. The integrated analysis of economic and environmental impact assessments is a valuable tool to guide sustainable waste management aligned with nations' targets.

S5 (40% Rcy) and S6 (95% IntF) are situated in Q1 (most eco-efficient), while S2 (80% SL), S3 (3 TWtE), and S4 (ZOL) are located in Q4 (environmentally-efficient). S2 (80% SL) presents a quadrant shift from Q4 to Q1 when more than 20% of the collected landfill gas is converted to electricity. NS1 (55% SL, 5% Comp, 40% Rcy) is the most eco-efficient among the four newly designed scenarios (NS1, NS2, NS3, NS4). NS1 is more cost-effective than S5 (40% Rcy) and S6 (95% IntF), indicating that it is unnecessary to divert all food waste from landfills. NS4 (2% SL, 1% Comp, 17.5% Rcy, 79.5% Icn) located in the lowest region in Q4 implies that treating 79.5% of waste in incineration is not the best eco-efficient MSW treatment system.

It is crucial to emphasize that the methane emissions for open and sanitary landfills are estimated using the IPCC First Order Decay method with the Tier 2 method. The activity data are country-specific, but the parameters adopted, such as half-life value or methane generation rate constant, are set based on the default. To obtain a high-quality methane generation value, parameters should be nationally developed or derived from site/country-specific parameters. The study's economic assessment only considers the capital cost, operating cost, and revenue gained from the value-added by-product. Gate fee and land cost are not considered. The exclusion of gate fees is due to the range of gate fees for all studied waste facilities that are not nationally developed, while the land cost could vary by location. The impact of gate fees and the land cost may be overlooked. Future studies could optimize the treatment location and gate fees. Sustainable solid waste management necessitates a comprehensive evaluation that includes social implications. Future research should also focus on identifying the best sustainable solid waste treatment system depending on local conditions by integrating environmental, economic, and social factors. This could help the government develop optimized and realistic waste treatment targets and enabling policies.

Credit author statement

Min Yee Chin: Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization, Writing – original draft; **Chew Tin Lee**: Supervision, Validation, Writing – review & editing; **Kok Sin Woon**: Supervision, Conceptualization, Resources, Validation, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The research data and their references are attached in Appendix A and Appendix B.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116238.

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