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ASSESSMENT OF WASTE MANAGEMENT SCENARIOS TOWARD MARINE PLASTIC DEBRIS MITIGATION AND COST REDUCTION

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Abstract

The increase in solid waste volume and change in composition due to urban development cause negative effects on the marine ecological environment. The aim of this study was to assess the amount of plastic waste leaking into the environment from the municipal solid waste (MSW) management system and propose mitigation measures towards sustainable development in Hue city, Viet Nam. The method of modelling MSW management system applying Material Flow Analysis (MFA) and simulating models through scenarios were used to propose strategic solutions to improve and develop the system. As a result, the implementation of segregation at source and improvement of the current collection system are urgently needed. Integrated treatment system including material recovery facility combined with transfer station, incineration, centralized and decentralized composting treatment can reduce the landfilled amount to 5% and the quantity of mismanaged plastic waste infiltrating the ocean has undergone a substantial reduction of several hundred-fold.

Keywords: marine plastic waste; material flow analysis; municipal solid waste management system; plastic waste reduction; sustainable development.

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1. Introduction

Plastic contamination pollution is currently a major environmental concern. In light of escalating and unsustainable levels of consumption, the global production of plastic surged to a staggering 360 million tons in 2018, marking a substantial 1.2-fold rise from 299 million tons within five years [1, 2]. Plastic bags and post-consumer plastic waste are increasing at an alarming rate in developing countries [3]. The primary causes of plastic pollution are the limitations of the municipal solid waste management system and the low rate of recycling activities [4]. The efficiency of waste management systems determines pollution and leakage of plastic waste [5, 6].

Marine plastic pollution (MPP), also known as "White pollution," has emerged as a global issue. South-East Asian countries account for more than half of the MPP's land-based sources [7]. According to the National Solid Waste and Plastic Waste Baseline Report, Vietnam ranks fourth in the world in terms of the annual amount of plastic waste discharged into the ocean [8]. According to the national report on solid waste management, over 64 thousand tons of domestic waste were generated daily in Vietnam in 2019, with urban areas accounting for 56% of total waste. Plastic waste accounts for 16 to 21% of total solid waste mass and contains 70 to 90% non-valuable plastic material [8]. Meanwhile, approximately 25% of all plastic waste created is recycled, mainly through informal sectors. Domestic waste has grown at a rate of 46% over the last decade. The collection system has been greatly

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improved, with a national collection rate of 92% in 2019. Landfilling is the most common treatment method, accounting for approximately 71% of total national domestic waste disposal, with sanitary landfills accounting for only 20% of total disposal [9]. The infrastructure system was not developed concurrently; the old MSW management system was unable to meet the recent rapid increase in solid waste. Waste pollution will inevitably have an impact on the environment.

In recent years, there has been a growing public awareness of the potential harm caused by improperly managed plastic debris, particularly marine litter [10, 11]. Material Flow Analysis application has risen over the previous several decades, and it has been applied to a wide range of materials and chemicals in various geographical regions. MFA was used to trace physical flows and stocks of mass plastic from fishing gear through use and post-use processes in Norway [12]; evaluate the amount of plastic recovered at the source, identified the amount of plastic waste recycled and proposed alternative solutions to improve plastic waste management in Jakarta [13]. As a first step in formulating a waste management policy in Malaysia, the Material Flow Analysis-Social Agent Analysis (MFA-SAA) decision was suggested [14].

A better understanding of plastic flows is critical for tackling the plastic waste problem by detecting inefficiencies, material losses, and potential leaks into natural systems. In Vietnam, MFA method was simulated to describe and analyse the current status of MSW system [15]. Despite the aforementioned fact, there is a lack of evaluations of the strategic solutions to improve and develop the system. Furthermore, to the best of our knowledge, an alternative appropriate waste stream management and feasible treatment technology scheme based on actual plastic waste material flow has never been proposed. The goal of this research is to create scenarios for urban-oriented waste management systems that reduce plastic wasted leaked to the ocean, as well as important information for national policymakers developing strategies to aid the attainment of national goals. Modeling aids decision-making by identifying viable treatment technologies and appropriate waste stream management.

2. Material and methods

2.1. Study area and management waste status

Hue is the capital of Thua Thien Hue province, located in the North Central Coast region of Vietnam. The city has a natural land area of 26,600 ha with a total population of 333,004 (in 2023) (Fig. 1).

In 2019, Hue city generated an average of 269 tons of solid waste per day, for which 98.2% of the generated waste is collected by Hue Urban Environment and Public Works Joint Stock Company (HEPCO) for landfilling (HEPCO, 2020). The residential, trading, and tourism industries produce the majority of the MSW. The MSW composition in Hue has been significantly changing in the last decade. As the plastic waste rate increased from 8.28% to 12.99%, the organic waste proportion declined from 84.01% in 2012 to 72.16% in 2018 [17]. These changes could be induced by urbanization, commercial and service development, and changes in daily living.

Hue city does not have source-segregated solid waste. The mixed waste is collected by carts, electric tricycles and trucks, and directly transferred to the landfill site. Thuy Phuong composting plant had been in operation since 2007 but this composting plant closed in 2018 [16] due to poor compost quality and treatment failure. The inefficiency of waste separation is one of the causes of the failure of urban-scale composting plants. The guideline for waste separation at source was given by Thua Thien Hue province on June 1, 2020, and the Plan for implementing solid waste segregation at source was issued by the Hue city government on March 25, 2021 [18, 19]. Solid waste must be separated into three categories: recyclable waste, hazardous waste, and other waste. The HEPCO will be in charge of collecting and transportation to the Phu Son incinerator plant, although burning the

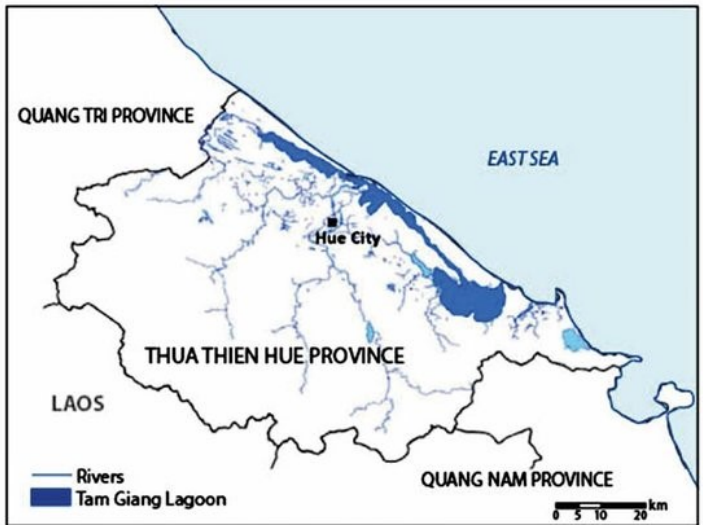

Figure 1. Map of Hue city [16]

MSW may face certain obstacles due to wet waste (biodegradable garbage accounting for more than 70% of total waste), humid air, and the extended rainy season each year.

Statistics over the past few years show that Hue City's MSW is changing in line with the global trend that Vietnam, Southeast Asia, and the entire world are recognizing. In this way, the waste generation coefficient and plastic waste rate is estimated to rise to a level that is roughly equivalent to that of first-grade cities. This makes it more important than ever for local and national action plans for managing plastic waste.

2.2. Identify key interventions for plastic waste management

a. Local experts survey

14 local experts were chosen to do a questionnaire survey about identifying effective strategies for enhancing MSW management in Hue. The local experts who were interviewed will be explained in Table 1. The chosen professionals are active in Hue city waste management system and have excellent knowledge and experience in environmental and solid waste management. The survey's content centered on how participants saw the viability of various interventions from their perspective and experience with reference to the regional socio-economic circumstances.

Table 1. Local experts selected for the questionnaire based survey

Stakeholder groups	Explanation of local experts
Waste producers *4 people*	Working in supermarkets, local markets and residents living in Hue city
Waste contractors *2 people*	HEPCO and waste recyclers operating in Hue city
Authorities *3 people*	Environmental managers, waste management specialists working in the city, ward people committee
Academic experts and NGOs *5 people*	Professors, researchers working in Universities and experts working in Non-Governmental Organization (NGOs) in Hue city

b. Data analysis method

The degree of consensus (DC) denoted the degree of similarity of preference among stakeholders, and the consensus results (CR) signified the average preference of related stakeholders. To calculate the consensus results and the degree of consensus, consensus analysis model (CAM) was applied [20]. The fuzzy set theory was conducted to deal with linguistic variables in CAM, employed to assess feasibility of interventions according to local experts' opinions. In this study, the compromise among all stakeholders is reached when the DC value is 0.3 or greater.

2.3. System model development

The MFA method is used to formulate a general model based on the waste stream of Hue city. The suggested model can identify the precise stream of each type of materials and capacity of treatment facilities based on the waste flow. The MSW system in Hue city's waste flow is shown in Fig. 2.

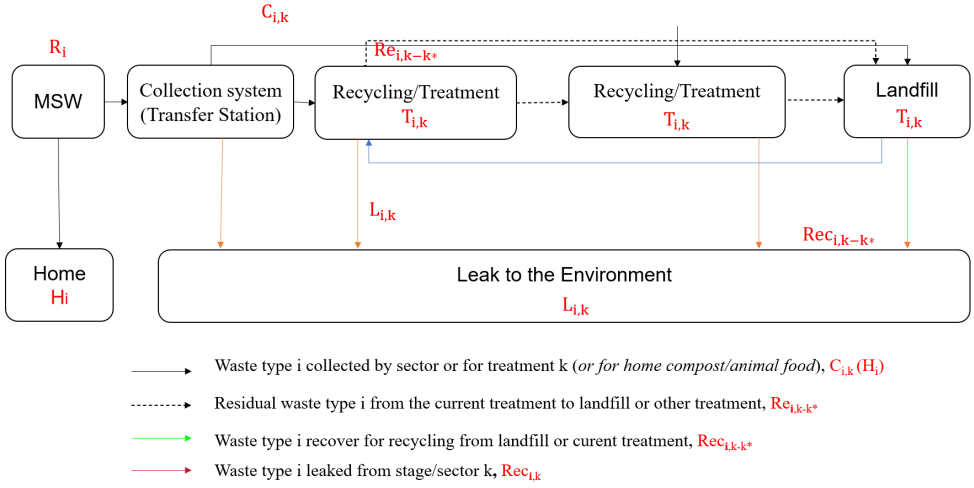

Figure 2. Diagram of waste material flow conceptual model of Hue city

The input data for the model including waste generation amount, collected amount and landfilled amount are secondary data, collected from HEPCO in 2020. Waste composition and informal recycling rate was referenced from survey results of World Widelife Fund (WWF) research group in Hue in 2020.

It should be noted that recycling is possible for four different types of materials, including paper, high valued plastic, metal, and glass. These materials can be collected separately by scavengers and junk buyers who engage in informal recycling activities by gathering recyclable materials from treatment plants, from collection points, or by purchasing directly from households. Also, a small number of households compost their own garbage at home or give it to their animals as organic material (food and garden waste).

Based on the current waste flow of Hue city, waste flow models were developed applying input-output analysis and mass balance principle and for each process [21].

The collection and transportation cost C_C was estimated by the Eq. (1):

$$C_C = c_c^t \times d_c \times W_c + C^{ts} + c_t^{ts} \times d_t \times W_t \quad (1)$$

where c_c^t is the collection unit cost, estimated based on the current collection cost reported by HEPCO in 2020, it is about 33000 VND per ton per km; d_c is the average distance from the city to transfer

station or treatment facility defined by the planned locations of facilities, presented in Table 2 (km); d_t is the average distance from the transfer station to treatment facility (Table 2) (km); W_c is the amount of waste collected by collection contractor of the city (ton); W_t is the amount of waste transported from transfer station to treatment facility (ton); c_t^{ts}: Transportation of waste from transfer station to treatment facility normally uses haul vehicles (big trucks of 25 tons or over). Thus, the unit cost for transporting waste is much cheaper, in this report the transportation unit cost of a haul vehicle (c_t^{ts}) was assumed as 20000 VND per ton per km; C^{ts}: The cost of transfer station operation [17]. A facility of 3000 m^2 site with six vehicles of 25 tons in capacity are chosen for the transfer station system, VND per ton.

Table 2. Distance from Hue city to treatment plant

Area	District/ Wards	Thuy Phuong Landfill	Phu Son treatment complex
Core	Hue	12	21
Expanded	Thuy Van	12	21
	Thuy Bang	8	19
	Thuan An	19	29
	Phu Thuong	16	25
	Phu Mau	20	29
	Phu Duong	18	27
	Huong Tho	10	20
	Huong Ho	16	27
	Huong Vinh	16	25
	Huong Phong	26	35
	Huong An	20	31
	Hai Duong	28	37

The treatment cost C_T was estimated by Eq. (2):

$$C_T = \sum_k c_k \times T_k \tag{2}$$

where c_k is the unit treatment cost of treatment k defined (VND per ton); T_k is the amount of waste treated by treatment facility k (tons).

2.4. Scenarios development

The key interventions chosen by experts contributed to waste management scenarios development. The scenarios were developed also based on the Solid Waste Management Planning of Thua Thien Hue province to 2030, vision to 2050, of the People's Committee of Thua Thien Hue province [18, 19] and Plan No. 237/KH-UBND issued on November 9, 2017 on Implementation of the above Plan [22]. Some plans issued by Hue city are also the basis for building scenarios for the urban solid waste management system in Hue until 2030.

Some common assumptions for all scenarios are: The waste generation/ contribution rate of waste sources, the waste composition and characterization, collection and treatment price (per ton) will remain unchanged in the future; The growth of the number of waste sources may lead to the increase of waste generation.

Table 3. Scenarios description

Business -as-usual (BAU SC)	The BAU SC simulates the urban waste flow in Hue city in the next 10 years without any changes
Scenario 1 (SC1)	SC1 was developed based on BAU SC with the assumptions: - The waste collection system should be improved and reach the general waste collection rate at 98% by 2025 - 2030. - The efficiency of waste separation at source will be 100% by 2025 - 2030, according to the plan No. 1729 issued on March 25, 2021 by the People's Committee of Hue city [19]. - Waste is separated at source to recyclable waste, biodegradable waste and other waste. However, the recycling system is based on informal activities such as home composting and informal sector with their current capacity.
Scenario 2 (SC2)	SC2 was developed based on SC1 with the assumptions: - Waste is separated from source to recyclable, biodegradable waste (for home compost) and other waste. - A Material Recycle Facility (MRF) and a transfer station (TS) is suggested and combined in the new Thuy Phuong treatment plant, the distance from Hue city to MRF/TS is 17 km, and the distance from MRF/TS to Phu Son complex is about 10 km. - Both informal sector and MRF recycling for recyclable waste, and degradable waste is composted at home or in small communities.
Scenario 3 (SC3)	SC3 was developed based on SC2 with the assumptions: - Waste is separated at source to recyclable, biodegradable waste (for home compost) and other waste. - Waste to energy (WTE) incinerator with a capacity of 400 tons per day in Phu Son treatment complex is added. - Both informal sector and MRF recycling for recyclable waste, and degradable waste is composted at home or in small communities. Other waste is burnt in WTE. A landfill for fly and bottom ash disposal inside the treatment complex.
Scenario 4 (SC4)	SC4 was developed based on SC3 with the assumptions: - Overall waste collection efficiency is 100%. - Waste is completely separated at source to recyclable, biodegradable waste and other waste. - A centralized composting plant is added. - Both informal sector and MRF recycling for recyclable waste. Beside home compost, separated at source degradable waste is transported to TS and then a centralized composting plant in Phu Son complex. The other waste is burnt in WTEAn assumption is made: 40% of degradable waste is recycled at source. 60% is collected by HEPCO and treated in a centralized composting plan (in Phu Son complex).

2.5. Softwares and analysis tools

The data for CAM and system cost estimation were processed using Microsoft Excel 365 and the MFA of waste flow in scenarios were modelled using the software STAN 2.7.101 version, developed at the Research Unit for Waste and Resource Management, TU Wien and Microsoft Excel 365.

3. Results and discussions

3.1. Key interventions for Hue city plastic waste management

Table 4. Results of analyzing the consensus on opinions contributed to key interventions for Hue city plastic waste management system by local experts

Relevance levels	CR	Cause groups	DC	Solutions	DC
Highly suitable/ Agree	0.875 - 1	The current price of single used plastic bags is too cheap	0.77	Stop providing single used plastic bags at markets and retailers	0.159
		Unsustainable consumption habits	0.48	Reusable products	0.698
				Stop providing single used plastic bags at supermarkets	0.308
				Do not produce and use single used plastic products	0.24
		Ineffective solid waste collection system	0.15	increaseing collection efficiency	0.394
Suitable	0.625 - 0.875	Inefficient treatment technology	0.39	Closed-loop recycling	0.285
				Open-loop recycling	0.338
				Burning waste for electricity	0.285
				Separate recyclable waste	0.416
		Inefficient recycling activities	0.36	Biodegradable wasterecycling	0.458
				Increase recycling products	0.396

The primary factor identified by a majority of stakeholder groups as the leading cause of marine plastic debris is the current pricing of single-use plastic products and the unsustainable consumption practices associated with them (DC = 0.77). Consequently, altering the behavior of individuals towards sustainable consumption emerges as a crucial strategy in mitigating plastic waste and marine plastic debris at its root. Nevertheless, implementing this approach necessitates a comprehensive long-term action plan that encompasses systemic changes. These changes involve strengthening the accountability of producers, developing alternative products to replace single-use plastics, and enhancing the waste management system.

The implementation of an effective solid waste management (SWM) system plays a crucial role in preventing the leakage of plastic waste into the ocean. However, stakeholders hold different perspectives on this matter based on their respective groups. Academic experts and contractors concur that an inadequate SWM system serves as a primary driver of marine plastic waste. Conversely, authorities and waste generator groups do not perceive it as a significant factor. The divergence in opinions regarding the role of the waste management system in contributing to marine plastic leakage in Hue city can be attributed to varying levels of stakeholder understanding concerning the SWM system.

The waste collection system currently in place in Hue city has proven to be highly efficient, with approximately 98% of the waste generated in the core area being successfully collected. This high

level of efficiency has led some local experts to believe that there is no need for further improvement in the waste collection system (DC = 0.15). However, it is important to recognize that the waste collection and transportation system is a crucial component of the overall waste management system, and its effectiveness directly impacts the efficiency of the entire system. This system plays a critical role in collecting and transporting different types of waste to the appropriate treatment technologies or facilities. Therefore, it is necessary to enhance the waste collection system in order to transition from a system that does not separate waste to one that does.

The ineffectiveness of certain treatment technologies is identified as a contributing factor to the leakage of plastic waste (DC = 0.39). Local experts suggest that waste incineration is a potential solution for reducing waste sent to landfills (DC = 0.285), despite its drawbacks of releasing harmful substances like dioxins and toxic subtances, and ash into the environment, as well as its high capital and operational costs. Additionally, the biological treatment of degradable wet waste (DC = 0.458) is seen as a promising intervention for the waste management system in Hue city. Both centralized and decentralized approaches to degradable waste treatment are deemed acceptable based on local conditions. However, it is crucial to take into account the lessons learned from the failure of the Thuy Phuong composting plant in order to develop an appropriate plan for the future municipal solid waste management system.

3.2. Result of scenarios estimation

a. Business-as-Usual Scenario (BAU SC)

The increased rate of domestic waste in Hue city is anticipated to be roughly 15% over a 5-year period [17]. Food waste will be recovered at a rate of 16%, while high-value recyclable materials would be collected at a rate of 3.2%. The remaining waste will be collected and transported to the landfill. The efficiency of the collection system will not be improved, and the limitation in segregation at source and recycling activities may not be able to reduce the loss of waste to the environment. Inevitably, about 5 thousand tons of waste will be leaked every year, including about 125 tons of plastic waste.

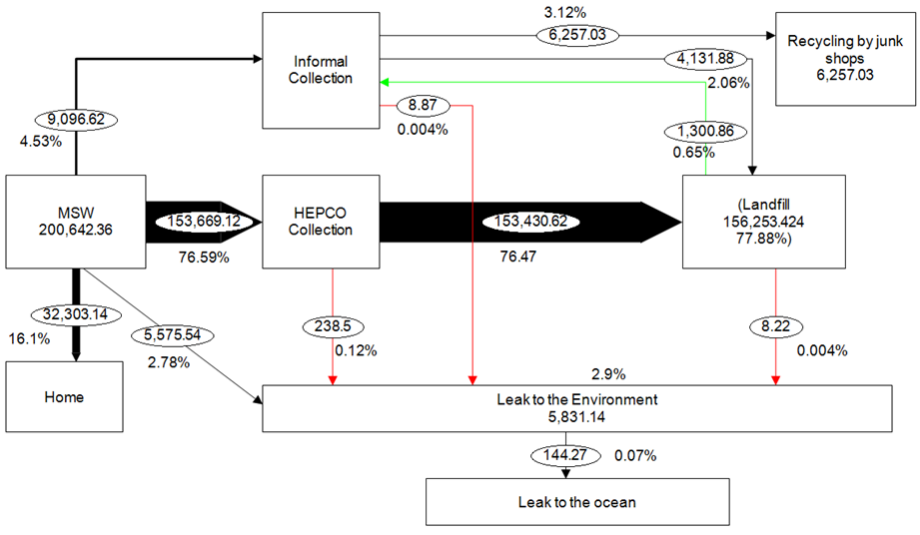

Figure 3. The waste flow of Business-as-Usual Scenario (BAU SC) in 2030

The BAU scenario does not appear to be compatible with the province's strategy for producing municipal solid waste and is not viable for achieving the targets established by the locality in Decisions

No. 1413 and 1414 published on June 23, 2016 [17]: The proportion of garbage for direct landfill shall be 0% by 2025, and the collection rate must be 100% by 2030.

b. Scenario 1 (SC1)

The amount of waste collected in the SC1 is higher than in the BAU because of the improvement of the waste collection system in Hue city. This may help to reduce the quantity of garbage that is released into the environment. Waste separation at the source appears to have made a significant contribution to increasing recycling procedures. When compared to the BAU model, the amount of high-value recyclable waste collected by the informal sectors in the SC1 grew over four times. Waste separation at source also creates opportunities for reducing organic waste (kitchen waste and garden waste) by composting at source, which was studied and pilot implementation in the last 5 years. This will positively contribute to minimizing the daily waste collected and improving the quality of waste for the final solutions. The highlight of the SC1 and SC1' is the significant reduction in the amount of plastic waste released into the environment. Whereby, the amount of plastic waste leakage will be reduced by 50% compared to the BAU.

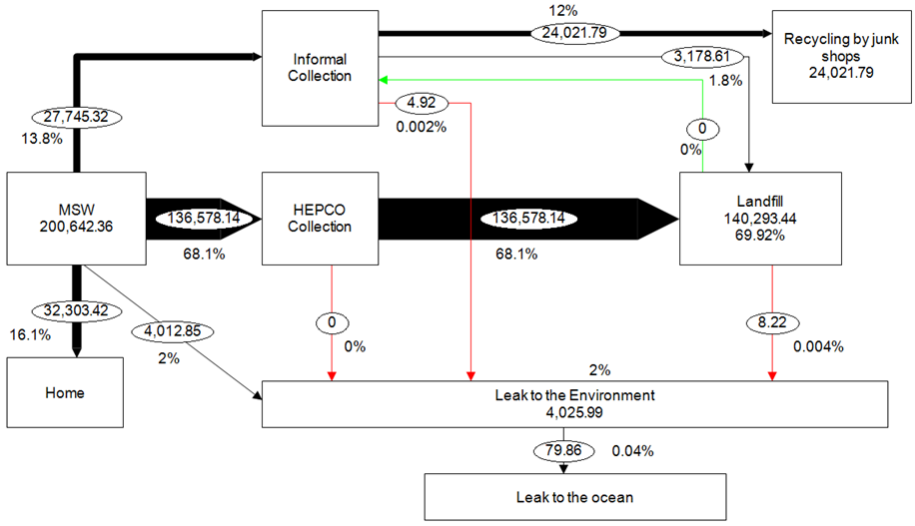

Figure 4. The waste flow of Scenario 1 (SC1) in 2030

These scenarios demonstrate their applicability and compatibility with Hue's existing municipal solid waste management situations. The projected outcomes of SC1 are also consistent with the goals of Hue, an environmental city program. Furthermore, integrated waste treatment should be considered in order to optimize the waste management system and lower the rate of landfilling. End-of-pipe recycling systems must be upgraded to handle the increasing volume of recyclable material collected daily, while simultaneously encouraging the growth of informal recycling activities. Finally, waste management communication and education should be done synchronously and continuously to improve waste separation at the source, which is an important stage in the municipal solid waste management system.

c. Scenario 2 (SC2)

Scenario 2 demonstrates the substantial contribution of centralized MRF when combined with TS to the Hue city collection system. In 2025, the cost of waste collection and transportation will fall from 118 billion VND (Scenario 1) to 106 billion VND. As a result, the cost of transportation by haul

vehicle transportation and transfer station is less than the cost of transportation by existing trucks. However, the change was not statistically significant.

Instead of landfills, the MRF redirected recyclable waste to a recycling facility or sold it to recyclers. As a result, the volume of recyclable garbage transported to landfills (formal recycling) decreased by approximately 19 thousand tons in 2025 and approximately 22 thousand tons in 2030. As a result, the cost of transporting recyclable waste can be ignored. Furthermore, by reducing the amount of waste delivered to landfills, the overall cost of the waste management system has been reduced by 16 to 21 billion VND in the period 2025 - 2030 when compared to Scenario 2 and BAU.

The SC2 assists Hue in meeting the PSC target by reducing leaking plastic waste by more than 30% compared to BAU (from 125 to 69 in 2025 and 144 to 80 in 2030). However, it cannot directly reach the sustainable solid waste management target of a city type stated in the National waste management policy (Decision 491/QD-TTg) [23], which is less than 30% trash landfilled.

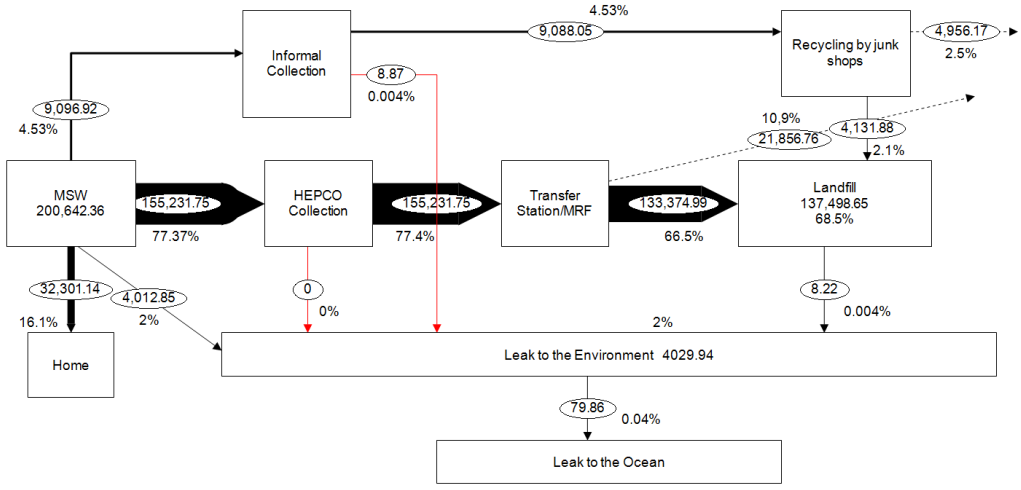

Figure 5. The waste flow of Scenario 2 (SC2) in 2030

d. Scenario 3 (SC3)

In the SC3, a WTE incineration is operational in 2025, resulting in a considerable shift in the city's waste flow and waste management system: WTE incineration increased the system cost significantly compared to SC2. The cost of treatment has grown to twice that of SC2. In 2030, the amount of waste sent to landfill dropped drastically to around 30 thousand tons. It accounted for around 15% of total garbage generation that was landfilled. As a result, no waste is directly landfilled in the city, and the total amount of waste landfilled is less than 20%. The national aim established in Decision 491/QD-TTg [23] has been met. Similarly, the amount of plastic waste leaking into the sea is almost equal to SC2 and accounted for about half of the BAU scenario, achieving the target of PSC.

However, biodegradable waste, such as food and garden waste with high moisture content and low calorific value, accounts for the majority of the waste burnt in SC3. According to the waste flow analysis, there are 320 tons of degradable waste (85%) in 380 tons of waste burned in the WTE incinerator. Due to the high moisture content of biodegradable waste, the waste mixture has low calorific values, resulting in low economic and environmental efficiency of WTE incineration.

In Viet Nam, the lower-heating value of degradable waste ranged from 2000 J/kg to 2500 J/kg [20]. With 85% degradable percentage in waste as SC3, the heating value of the mixture hardly exceeds

5000 J/kg. As a result, it is critical to have a pre-treatment procedure that minimizes the amount of water and raises the heating value of the waste mixture before incineration (to more than 7000 J/kg for WTE). Otherwise, operational costs will skyrocket due to increased fuel use and air pollution control.

Furthermore, the ash percentage of biodegradable waste (approximately 19%) [20] is higher than that of other combustible waste, resulting in a greater volume of ash residuals after incineration. To be more efficient in WTE incineration application in Hue city, it is necessary to reduce degradable waste from combustion waste.

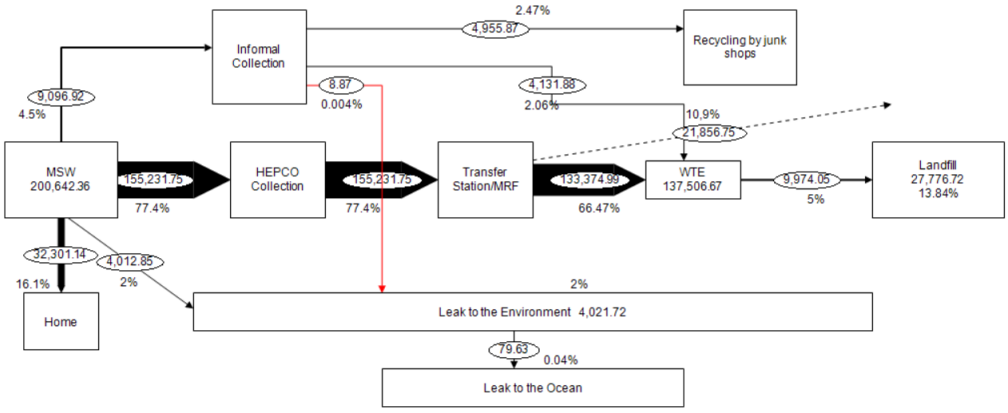

Figure 6. The waste flow of Scenario 3 (SC3) in 2030

e. Scenario 4 (SC4)

The SC4 encourages the separation of biodegradable waste from combustion. As a result, incinerated waste is reduced to 60 tons per day, while landfilled waste is reduced to roughly 27 tons per day. Because less waste is consolidated in SC4, the system cost is substantially lower than in the prior three scenarios. 40% of degradable waste is recycled at the source through home and small community composting, as well as animal feeding. In a centralized composting system, only 60% of degradable waste will be composted. SC4's waste management system costs around 150 billion VND, which is significantly less than other scenarios.

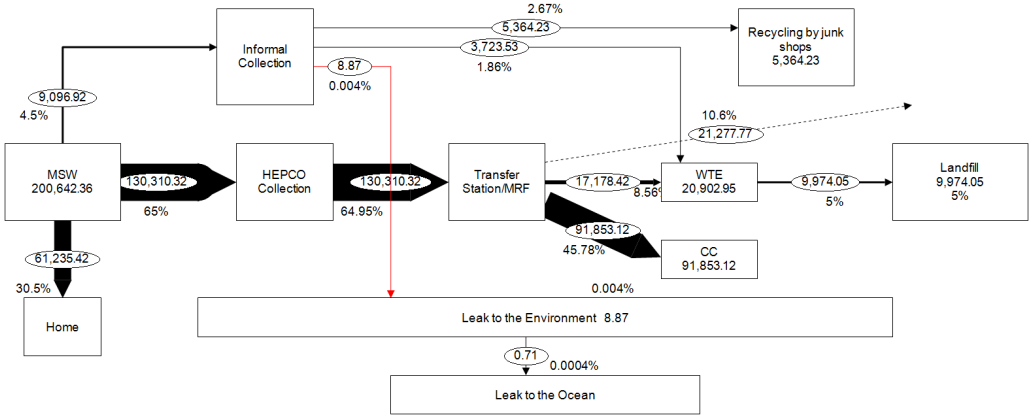

Figure 7. The waste flow of Scenario 4 (SC4) in 2030

Diverting the degradable waste stream away from incineration is recommended to improve the economic and environmental efficiency of the waste management system. However, waste incineration requires a consistent and substantial amount of waste input to ensure long-term functioning. A daily capacity of 60 tons is insufficient to power the projected incinerator in the Phu Son facility. As a result, in terms of incinerator application, this scenario will collide with Hue City's current waste management strategy.

The greater collecting efficiency resulted in nearly no plastic waste leaking into the ocean. Thus, increasing the capacity of collecting systems is critical for reducing ocean plastic waste.

3.3. Scenarios assessment

The outcomes of the SC1 and BAU scenarios demonstrated that waste segregation at the source would be insufficient without investment in other functional components of the MSW management system, such as collection and treatment facilities. The operation cost of SC1's waste management system is barely cheaper, but the difference is not statistically significant (Fig. 8).

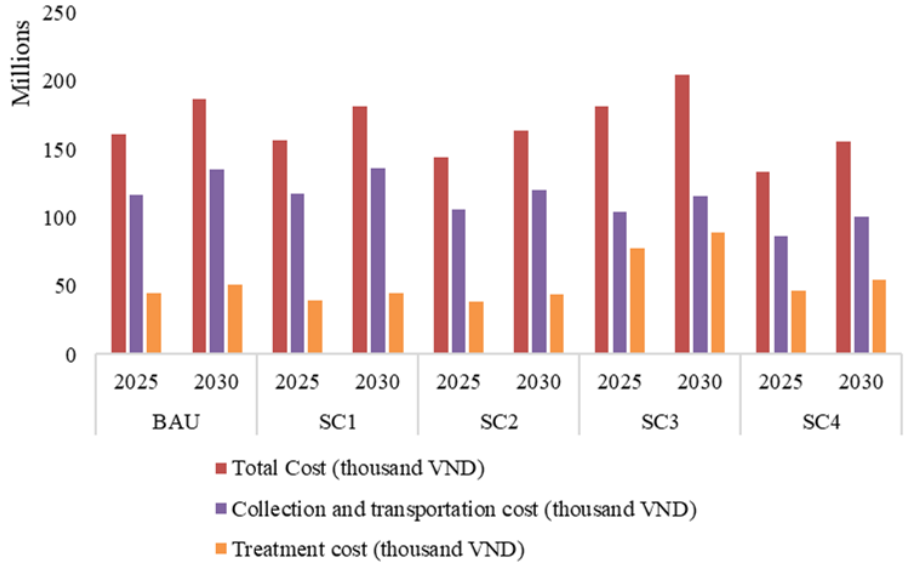

Figure 8. The cost of the waste management system in different scenarios

The SC2 demonstrates the effectiveness of TS and MRF by saving more than 20 billion VND for the waste management system as compared to the BAU scenario (Fig. 8). Waste transfer stations are an essential part of efficient solid waste transportation. Transferring waste from local pickup trucks to larger vehicles or other modes of transportation minimizes transportation costs to distant disposal sites. It also allows collection-specific trucks and employees to concentrate their time to community-based collecting efforts. Unloading garbage trucks, screening, and removing prohibited goods, compacting loads, and reloading onto larger vehicles are all possible tasks at the waste TS.

Material recovery facilities, landfills, resale shops, and localized mechanical biological treatment facilities are sometimes co-located with transfer stations. In SC2, the TS is co-located with the MRF to transition to single-stream recyclable waste management. Plastic, paper, cardboard, metal, and glass is all recyclable in Hue. As a result, the MRF will combine those wastes into a single substance, which can subsequently be transferred to other locations or recycled in the MRF.

Glass is separated from other recyclables thanks to a contract with a glass producer, according to Plan no. 1729/KH-UBND [19]. As a result, the MRF may sort glass further or just store glass waste

before transporting it to the glass recycling plant. Glass is typically classified by color, with clear, green, and brown glass being more valued on the commodities market than other colors of glass. Glass can be crushed into minute fragments, known as cullet, and sold to manufacturers that re-melt it and transform it into new glass items or use it as insulation.

Other recyclable waste must be sorted in order to improve their value in supply chains. Separation and sorting technologies for paper and plastic in MRFs could help in the separation of these materials into single-stream material for recycling or sale to other recyclers. Low-value plastic and recyclable material that other recyclers may not be interested in can become input material for the manufacturing of refuse-derived fuel (RDF). The RDF can be sold to a local cement kiln as fuel for their production.

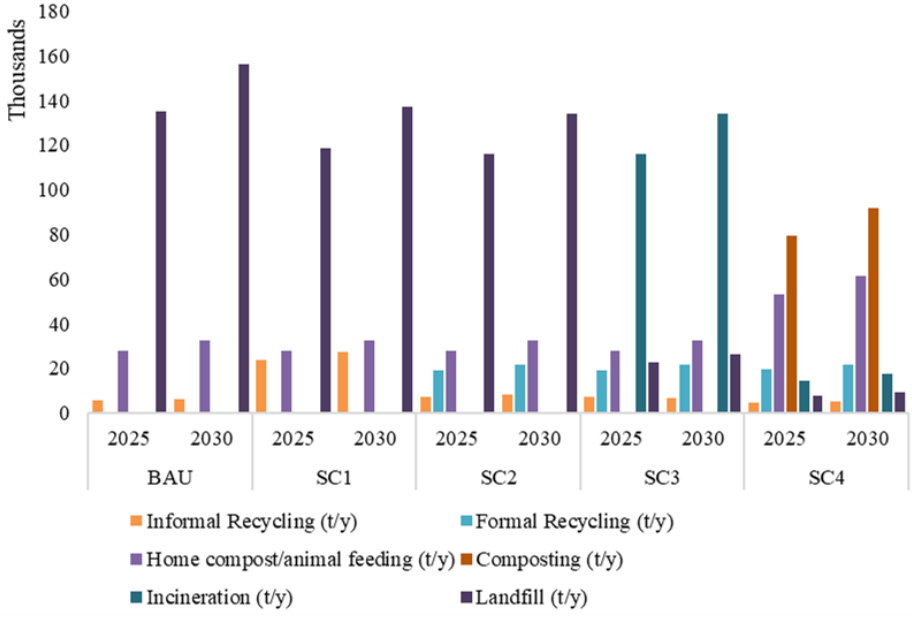

Figure 9. Scenarios comparison

However, due to the composition of the waste intake, the use of WTE incineration in SC3 is risky. Wet waste (degradable waste) accounts for 85% of waste for combustion, which might have an adverse effect on the waste mixture's heating value. As a result, a pre-treatment method for dewatering waste and controlling the heating value of waste is critical.

Furthermore, automatic air pollution monitoring and fuel loading are critical for WTE incinerator combustion process control. It keeps the combustor temperature stable and reduces air pollution emissions such as dioxin and furan. However, because it necessitates more fuel usage to optimize the combustion process, this technique is more expensive for incineration operations. With an automated controlling system, the operational cost can reach around 2 million VND per ton, which could be minimized by ignoring this technology when the stated price was just 600 thousand. An automated emission air monitoring and automatic fuel loading system is recommended for incineration in Hue City.

The SC4 scenario appears to be the best choice in terms of both economics and the environment. However, due of the failure of Tam Sinh Nghia technology, investing in a centralized composting facility in Hue city is an essential question. Composting technology applications necessitate the presence of a local compost product consumption market as well as a high-quality degradable waste input. As a result, a market analysis is required to estimate the potential of the compost goods market and the

capacity of the composting plan.

Furthermore, the amount of waste burnt in SC4 is insufficient for efficient functioning. A significant amount is required for successful operation of the incinerator. As a result, combining SC3 with SC4 may be a viable approach. In this case, the composting capacity is determined by market demand, and the remaining biodegradable waste is burnt.

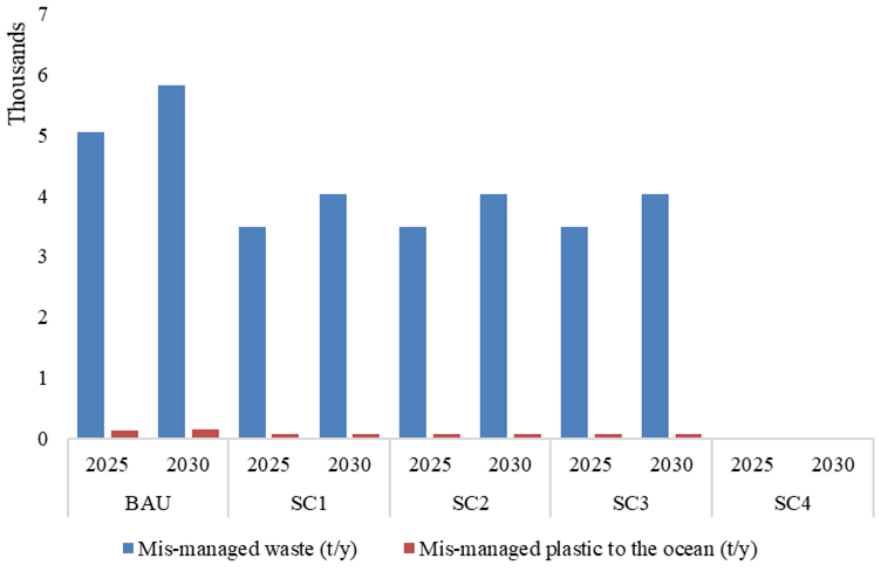

Figure 10. The mis-managed waste and mis-managed plastic to the ocean in different scenarios

4. Conclusions

The research team has developed a model to calculate these scenarios and provide quantitative results on the economic and environmental effectiveness of implementing the scenarios. The evaluation and comparison of scenarios shows that there is no perfect scenario for Hue city's solid waste management system, but it is necessary to take a roadmap of the necessary steps to improve and enhance the system. Specific solutions and roadmap for implementing solutions are proposed for the city. Implementing separation at source and improving the city's current collection system needs to be implemented immediately (SC1 scenario). After that, an incinerator must also be built immediately to ensure that waste has a place to be processed. However, the incinerator capacity needs to be reevaluated to ensure optimal volume and composition of waste burned. After that, a waste transfer and recycling station, as well as a solid waste treatment plant using centralized aerobic composting method, also need to be invested in and built. Implementing the above solutions helps the city achieve the goals of a class 1 urban area as stipulated in Decision 491/QD-TTg [23] or the goals of consumption or sustainable development.

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