Sustainable Plastic Waste Management Using a System Dynamics Approach

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Abstract

The exponential population growth coupled with rapid industrialization and urbanization triggered enormous generation of municipal solid plastic waste (MSPW). The massive generation of MSPW, coupled with the poor management, have caused significant negative impacts on the environment. Recently, a variety of MSPW management measures, such as source separation and plastic reduction, have been developed worldwide to guide MSPW management systems towards sustainability. Hence, developing a sustainable MSPW management system, through the application of advanced waste measures, is important for future sustainable development. However, sustainable MSPW management systems have not been well addressed in the literature. Therefore, this study aims to develop a generic system dynamics (SD) model to study the sustainable MSPW management. This is achieved through forecasting the effects of sustainable measures, namely source separation policy, recycling process, and incineration with energy recovery technology on MSPW management and amount of GHG reduction. The proposed model is implemented on a case study of MSPW management system in Dubai to assess its applicability and effectiveness. Vensim® software is used to stimulate and analyze the model through testing five different scenarios. The simulation results indicated that scenarios HSLRWI and LSHRLI perform best in terms of the amount of plastic waste recycled, scenario LSWRHI leads to the highest amount of GHG reduction, and scenario LSHRLI gives the highest amount of incinerated plastic waste with energy recovery and least amount of plastic waste landfilled. Therefore, the proposed model helps decision makers in choosing the scenario that works best according to their strategies and goals.

Keywords
System dynamics, Municipal solid waste management, Plastic waste.

1. Introduction
Municipal solid waste (MSW), defined as wastes generated from residential, commercial, institutional, and municipal activities, has been considered as one of the most significant problems facing urban city in transitional and developing economies (Coffey and Coad 2010, Karak et al. 2012). The exponential population growth coupled with rapid industrialization and urbanization triggered enormous generation of MSW, including plastic waste (Ayomoh et al. 2008).

The favorable physical and chemical characteristics of plastics (e.g., flexibility, durability, resistance to erosion, ease of processing, lightweight) contribute to its utilization in several commercial and industrial applications (Evode et al. 2021). In 2018, around 396 million tons of plastics were produced worldwide. This amount is expected to double in the following 20 years (Boyle and Örmeci 2020). However, the massive consumption of plastics, coupled with the poor waste management, have led to diverse environmental problems (Evode et al. 2021). Environmental pollution by plastic waste can contaminate and harm the terrestrial environment, which can be transferred to the aquatic environment, posing a serious threat to marine ecosystem (Alabi et al. 2019). In addition, the emission of greenhouse gases (GHGs) during the decomposition of plastic wastes in landfills is also a major concern (Shams et al. 2021).

Consequently, global efforts are now in force to guide MSW management systems, including municipal solid plastic waste (MSPW) management, towards sustainability. For instance, both the Sustainable Development Goals and the Global Waste Management Goals aim to reduce waste generation by 2030 through waste prevention, reduction, recycling, and reuse (Wilson and Velis 2015). Furthermore, various MSPW management measures and initiatives have been developed and are now included in modern systems worldwide to account for the negative environmental impact of MSPW.

Accordingly, it is imperative to understand the impact of integrating sustainable measures in the MSPW management systems. However, sustainable MSPW management systems have not been well addressed in the literature. While many previous studies evaluated the effect of waste measures and policies on MSW management in general, none of them has studied how these measures affect the MSPW management and its corresponding environmental effects.

1.1. Objectives

Under the previous circumstances, this study aims to develop a system dynamics (SD) model to study the sustainable MSPW management. This is achieved through forecasting the effects of sustainable measures, namely source separation policy, recycling process, and incineration with energy recovery technology on MSPW management and amount of GHG reduction. The impact of these sustainable measures is stimulated through conducting different scenarios. The proposed SD model is aimed to be generic and useful across different countries and cities.

2. Literature Review

The earlier MSPW management techniques were inadequate. Since 1950, nearly half of plastic has ended up in landfill, which has been considered as the most undesirable management technique due to its negative environmental impact. The plastics' interaction with toxic substances in landfills can produce toxic leachate and deteriorate the surrounding land (Zhang et al. 2021). Therefore, municipalities in several countries around the world have either imposed mandatory policies or recommended voluntary measures to control MSPW.

Mandatory waste management policies include MSW separation at source system, which has been applied in multiple countries, such as Germany. This policy has proven to help in reducing the amount of MSW landfilled and enhance the recycling rate. In this system, people are expected to sort the generated MSW into different bin based on the waste's type. Furthermore, Extended Producer Responsibility (EPR), in which manufacturers are responsible for the environmental impacts of their products throughout their life cycle, has been established for end-of-life packaging (e.g., plastic containers) in many countries, such as Germany (Schroeder and Jeonghyun 2019). In addition, many countries have banned single use plastic bags, such as South Korea, which specified a fine up to 3 million won (£2,100) for violating the ban (Jang et al. 2020).

On the other hand, there are many examples of voluntary MSPW measures. For instance, Sweden has applied a deposit-refund system for polyethylene terephthalate (PET) bottles to help reduce their consumption (Zhou et al. 2020). Pay-As-You-Throw (PAYT) mechanism has also been widely used in countries like Germany, in which city dwellers are charged depending on the generated waste amount (Schroeder and Jeonghyun 2019).

Furthermore, due to the recycling technology's environmental efficiency, economic benefits, it has received widespread attention worldwide (Okan et al. 2019). For example, Germany is focusing on improvement of recycling, particularly, of single-use plastics (Schroeder and Jeonghyun 2019). Energy recovery (Waste-to-energy) technology, which is defined as the process of generating energy from incinerating nonrecyclable or economically unprofitable plastic waste, has also been widely promoted by many governments around the world, such as South Korea (Zhang et al. 2021). In addition to reducing the CO_2 emission, the use of plastic waste as alternative fuel will achieve high economic value due to the huge amount of energy generated (Singh and Sharma 2016).

To test the impact of these measures and policies on waste management systems, system dynamics has been widely used in several literature and studies. For example, Xiao et al. (2020) developed an SD model to simulate the impacts of different policies, including economy, demography, and MSW management policies on the entire MSW management for Shanghai, China. Sukholthaman and Sharp (2016) has also used SD to evaluate the influence of effective source separation on waste collection and transportation.

3. Methods

In this study, a system dynamics modeling approach is used to examine the impact of source separation policy, recycling process, and incineration with energy recovery technology on the MSPW management and the amount of GHG reduction. The following sub-sections discuss the methodology in detail.

3.1. System Dynamics (SD)

System dynamics (SD), a well-established modeling and simulation methodology, was originated by Jay Wright Forrester in 1958 for long-term decision-making analysis of industrial management problems (Chaerul et al. 2008). SD is particularly suited for complex systems such as a waste management system, as it includes several variables with interrelationships having variable values over a period of time (Al-Khatib et al. 2016). It is capable of analyzing the complexity, non-linearity, and feedback loop structures in physical and non-physical systems (Forrester 1994).

SD simulation supports exploring ‘‘what-if” scenarios analysis and testing various policies (Richardson and Otto 2008). Consequently, SD is frequently used for examining the relationship between the system’s behaviors over time and its underlying structure and decision rules (Wolstenholme 1990). The variables in the SD model are classified as stocks, flows, and auxiliary variables. In order to form the SD model for application, it is required to construct Causal Loop Diagram (CLD) and Stock Flow Diagram (SFD).

3.2. Causal Loop Diagram (CLD)

The CLD is an important tool for exhibiting the feedback structure of the system (Chaerul et al. 2008). The CLD shows how the variables’ interactions dynamically affect the system (Yuan 2011). The diagram includes causal links, which are arrows linking different elements together. Each causal link is assigned a polarity, either positive (+) or negative (-). If the causal link has a positive sign, then the variable increases or decreases in line with the arrow variable, whereas the negative sign on the causal link means that the variable goes in the opposite direction of the arrows (Yao et al. 2018).

The structure of the MSPW management model is illustrated in Figure 1. Gross Domestic Product (GDP) and GDP growth rate are considered in the economic subsystem. The demographic subsystem considers the population and the population growth rate. In MSW generation subsystem, total MSW generated is determined by the MSW per GDP per capita, GDP from the economic subsystem, and the population from the demographic subsystem. Since this study focuses on MSPW, the MSW is classified into plastic and other types of MSW. In the waste source separation subsystem, the MSPW is either separated at source or collected together with other types of MSW. The source-separated plastics will be transferred to the recycling process. However, the unseparated plastics go through a post-collection separation process, in which they are separated into recyclable and nonrecyclable plastics. In the waste treatment and disposal subsystem, the recyclable plastics go to recycling, while the nonrecyclable plastics must be either incinerated with energy recovery or landfilled. Recycling and incineration with energy recovery both contribute to the reduction of GHG emission.

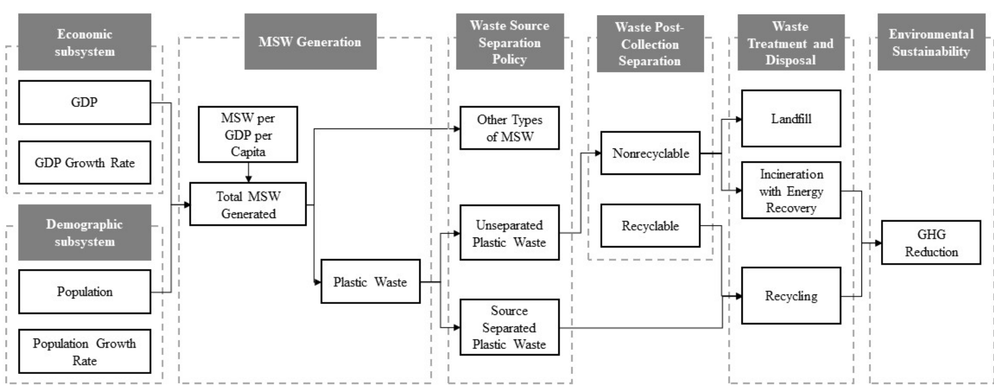

Figure 1. Structure of the system dynamic model for MSPW management

Based on this structure, the architecture of the CLD can be developed as in Figure 2. The MSW per GDP per capita, GDP, and population have positive polarity on total MSW generation. The increase of total MSW generation and plastic percentage of MSW will increase the plastic waste, which along with the source separation percentage, have a positive impact on the source separated plastic waste. The increase of the source separated plastic waste will increase the recycling amount of source separated plastic waste. In addition, recycling amount of source separated plastic waste, recycling amount of unseparated recyclable plastic waste, and incineration with energy recovery amount, all have a positive impact on the net GHG reduction amount.

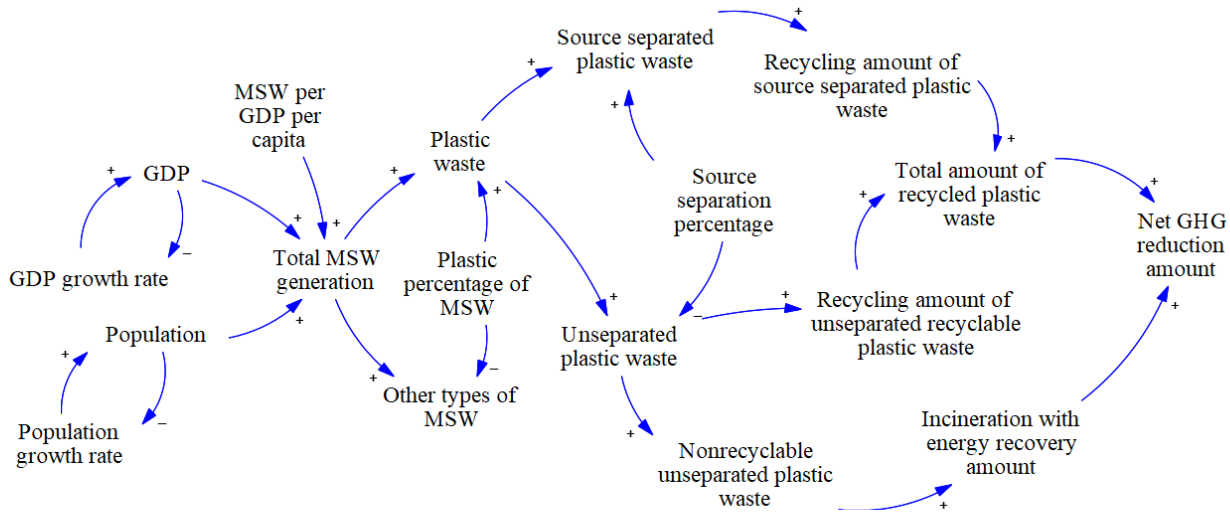

Figure 2. The proposed model's causal loop diagram

3.3. Stock and Flow Diagram (SFD)

Based on the CLD, all the key variables required are identified. Then using the Vensim® software, the conceptual CLD is then converted to a stock and flow diagram (SFD) as shown in Figure 3. The SFD, which tracts the stock and flow, highlights the system's physical logistics structure. The flow refers to the change in the stock. In the SFD shown in Figure 3, there are two stocks illustrated as rectangle boxes. The other variables in the model are auxiliary variables, which describe and simplify the model. An equation is assigned to each stock, flow, and auxiliary variable in the SFD. The dependent variables descriptions and equations are all tabulated in Table 1.

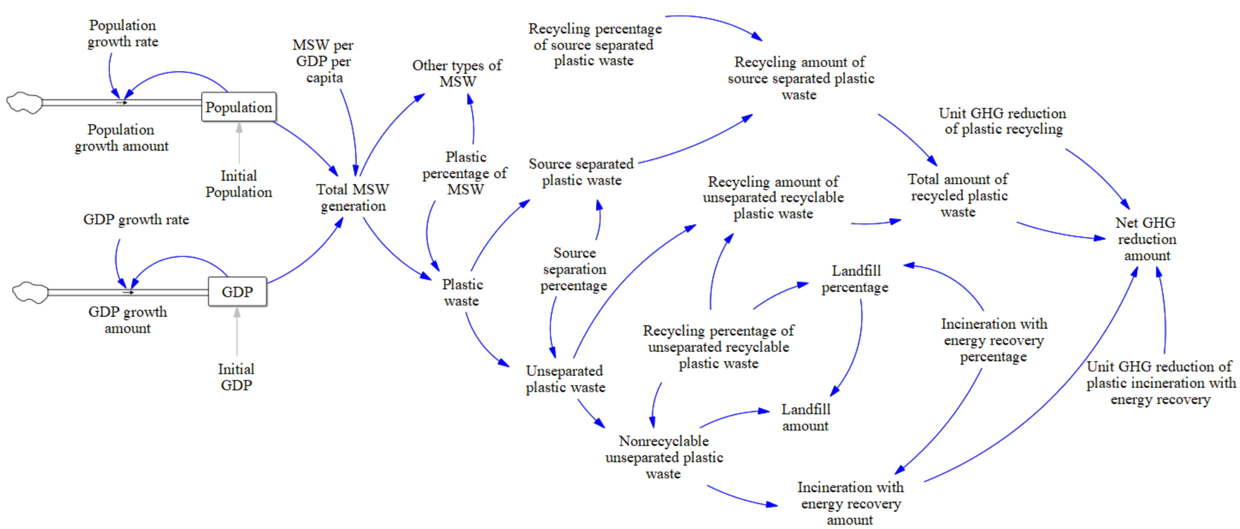

Figure 3. The proposed model's stock and flow diagram

Table 1. Dependent variables' equations and units

Variable	Unit
Population growth amount = Population growth rate * Population	Person/Year
Population = INTEG (Population growth amount)	Person
GDP growth amount = GDP growth rate * GDP	AED/Year

GDP = INTEG (GDP growth amount)	AED
Total MSW generation = MSW per GDP per capita * GDP * Population	tonne
Plastic waste = Total MSW generation * Plastic percentage of MSW	tonne
Other types of MSW = Total MSW generation * (1-Plastic percentage of MSW)	tonne
Source separated plastic waste = Plastic waste * Source separation percentage	tonne
Unseparated plastic waste = Plastic waste * (1-Source separation percentage)	tonne
Recycling amount of source separated plastic waste = Source separated plastic waste * Recycling percentage of source separated plastic waste	tonne
Recycling amount of unseparated recyclable plastic waste = Unseparated plastic waste * Recycling percentage of unseparated recyclable plastic waste	tonne
Total amount of recycled plastic waste = Recycling amount of source separated plastic waste + Recycling amount of unseparated recyclable plastic waste	tonne
Nonrecyclable unseparated plastic waste = Unseparated plastic waste * (1 - Recycling percentage of unseparated recyclable plastic waste)	tonne
Incineration with energy recovery amount = Nonrecyclable unseparated plastic waste * Incineration with energy recovery percentage	tonne
Landfill percentage = 1 - Recycling percentage of unseparated recyclable plastic waste - Incineration with energy recovery percentage	Dmnl.
Landfill amount = Nonrecyclable unseparated plastic waste * Landfill percentage	tonne
Net GHG reduction amount = (Total amount of recycled plastic waste * Unit GHG reduction for plastic recycling) + (Incineration with energy recovery amount * Unit GHG reduction for plastic incineration with energy recovery)	$MTCO_2E$

3.4. Case study and data collection

In order to evaluate the effectiveness and applicability of the proposed model, a case study of MSPW management in Dubai is conducted. Dubai is the most populous and the second largest Emirate in United Arab Emirates (UAE) with an area of 3,885 km^2 (Smail 2018). In the past decade, the rapid economic development, coupled with the population growth, triggered enormous generation of MSW, including plastic waste (EcoMENA 2022). In 2017, plastic waste accounted for 33.66% of MSW, making it the largest component of MSW (Dubai Statistics Center 2022).

Recently, in line with the Integrated Waste Management Strategy 2021-2041, Dubai is leading the UAE into a new era of innovation in waste management, recycling, and energy conversion (The United Arab Emirates' Government Portal 2022). In addition, starting from July 2022, Dubai will impose a tariff on single-use bags to reduce the excessive use of plastics. By 2024, all single-use plastics will be completely banned in Dubai (Gulf Business 2022).

In order to collect the data required for running a quantitative analysis on the proposed SD model, several sources have been considered. Some variables, such as GDP, GDP growth rate, population, population growth rate, MSW per GDP per capita, and plastic fraction of MSW are obtained from government statistics and a semi-structured interview with the head of Waste Management department in Dubai Municipality. However, constant parameters, such as unit GHG reduction from recycling and unit GHG reduction from incineration with energy recovery, are collected from previous literature and government publications. The units, values, and sources of the quantitative variables in the model are shown in Table 2. Furthermore, the values of dependent variables, such as source separated plastic waste and landfill of plastic waste, are determined through other variables in related mathematical equations.

Table 2. Quantitative variable values

Variable	Value	Unit	Source
Initial population (in 2015)	2,446,675	Person	(Dubai Statistics Center 2022)
Population growth rate	0.012	1/Year	(Dubai Statistics Center 2022)
Initial GDP (in 2015)	391,342	Million AED	(Dubai Statistics Center 2022)
GDP growth rate	0.027	1/Year	(Dubai Statistics Center 2022)
MSW per GDP per capita	$3.32*10^{-12}$	tonne/AED/Person	(Dubai Statistics Center 2022)

Plastic waste percentage of MSW	24.96%	Dmnl.	(Dubai Statistics Center 2022)
Unit GHG reduction of plastic recycling	1.124	$MTCO_2E$/tonne	(EPA 2020)
Unit GHG reduction of plastic incineration with energy recovery	1.365	$MTCO_2E$/tonne	(EPA 2020)

3.5. Scenario analysis

To analyze the influence of the source separation policy, recycling process, and incineration with energy recovery technology, five scenarios are developed (Table 3). Scenario analysis will simulate how different values of source separation percentage, recycling percentage of unseparated recyclable plastic waste, and incineration with energy recovery percentage affect the MSPW management and GHG emission reduction. Three different values are considered to develop the different scenarios: 0%, 25% (low percentage), and 75% (high percentage). Table 3 shows the parameters' values for each scenario.

In the WSWRWI (Without Source-Separation - Without Recycling - Without Incineration with energy recovery), none of the three sustainable measures is implemented. This scenario is developed in order to examine the potential dynamics of the system. However, WSLRLI (Without Source-Separation - Low Recycling - Low Incineration with energy recovery) aims to show the influence of implementing recycling and incineration with energy recovery technologies at low percentages. LSWRHI (Low Source-Separation - Without Recycling - High Incineration with energy recovery) is designed to stimulate the effect of implementing source separation policy at a low percentage, while applying the incineration with energy recovery technology at a high percentage. However, HSLRWI (High Source-Separation - Low Recycling - Without Incineration with energy recovery) aims at examining the effect of applying the source separation policy at a high percentage, while employing the recycling process at a low percentage. Finally, LSHRLI (Low Source-Separation - High Recycling - Low Incineration with energy recovery) is designed to evaluate the impact of implementing both source separation policy and incineration with energy recovery technology at low percentages, while applying the recycling process at a high percentage.

Table 3. The values of the parameters in different scenarios

Parameter	Scenario				
	WSWRWI	WSLRLI	LSWRHI	HSLRWI	LSHRLI
Source separation percentage	0	0	25%	75%	25%
Recycling percentage of unseparated recyclable plastic waste	0	25%	0	25%	75%
Incineration with energy recovery percentage	0	25%	75%	0	25%

4. Results and discussion

This section will first present the simulation results of the five different scenarios. The proposed SD model is run over a period of 25 years, starting from 2015 (Year = 0) till 2040 (Year = 25). Additionally, this section discusses the series of tests required to check the validity of the proposed SD model.

4.1. Model simulation results

The simulation results with different scenarios were analyzed based on four types of outputs: (1) total amount of MSPW recycled, (2) amount of MSPW incinerated with energy recovery, (3) amount of MSPW landfilled, (4) and GHG reduction amount.

The total amount of MSPW recycled comprises of the recycling amount of source separated plastic waste and the recycling amount of unseparated recyclable plastic waste. Figure 4 presents the results from the simulation of the five scenarios regarding the total amount of recycled plastic waste.

In HSLRWI and LSHRLI, the total amount of recycled plastic waste is at its highest throughout the 25 years reaching 1,692,050 tonnes in 2040. The high percentage (75%) of source separation in HSLRWI and recycling percentage of unseparated recyclable plastic waste in LSHRLI, has resulted in huge recycling amount of recycled plastic waste. Furthermore, WSLRLI and LSWRHI scenarios lead to the same amount of recycled plastic waste, reaching 520,632 tonnes in 2040. The total amount of recycled plastic waste in WSLRLI and LSWRHI are 69.23% less than the amount in HSLRWI and LSHRLI. However, the total amount of recycled plastic waste appears to be zero in WSWRWI scenario, as all the plastic waste ends up in landfill. The above results indicate that source separation and recycling measures are equally significant in increasing the amount of waste recycled. Therefore, in terms of the total amount of recycled plastic waste, HSLRWI and LSHRLI give the best results.

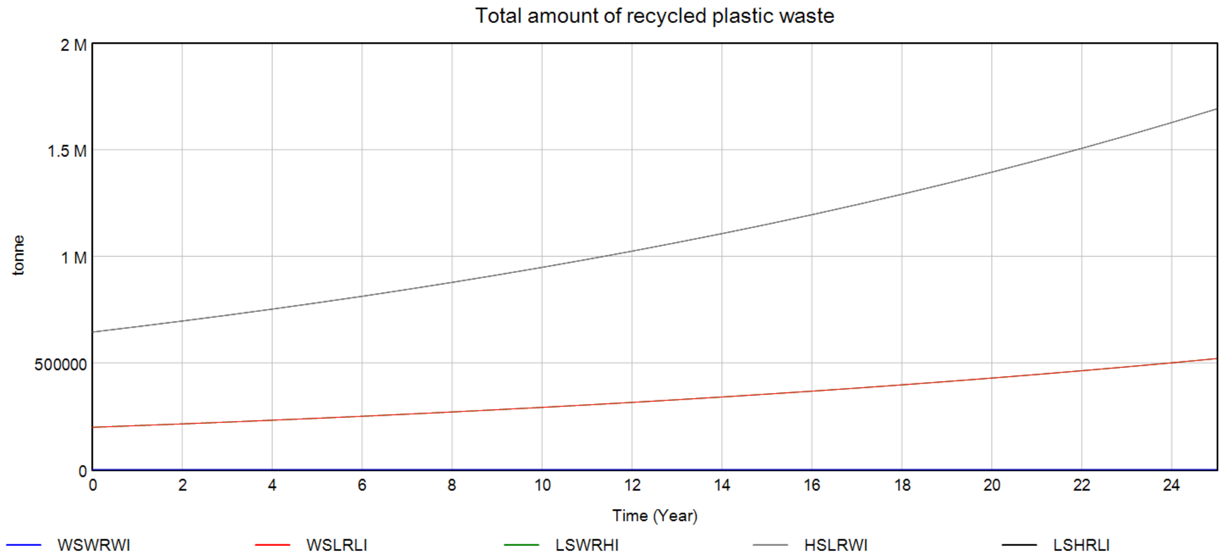

Figure 4. Total amount of recycled plastic waste for five scenarios

Furthermore, as shown in Figure 5, the amount of waste incinerated with energy recovery is at its highest throughout the 25 years in LSWRHI, reaching 1,171,420 tonnes in 2040. This is due to the high percentage of incineration with energy recovery applied in this scenario (75%). However, the amount of waste incinerated with energy recovery in WSLRLI is 66.67% less than the amount in LSWRHI. Moreover, in LSHRLI, the amount of waste incinerated with energy recovery is about 75% less than the amount in WSLRLI. However, the amount of incinerated with energy recovery waste appears to be zero in WSWRWI and HSLRWI, as all the nonrecyclable unseparated plastic waste ends up in landfill. Therefore, taking into consideration incineration with energy recovery amount, LSWRHI gives the best results.

Additionally, as shown in Figure 6, the amount of plastic waste landfilled is at its highest throughout the 25 years in WSWRWI, reaching 2,082,530 tonnes in 2040. This is because all the plastic wastes end up in landfill when the source separation, recycling, and incineration with energy recovery percentages are all equal to zero. However, the amount of waste landfilled in WSLRLI is 62.5% less than the amount in WSWRWI. Furthermore, in LSWRHI, the amount of plastic waste landfilled is 50% less than the amount in WSLRLI. Additionally, the amount landfilled in HSLRWI is 25% less than the amount of LSWRHI. However, the amount of plastic waste landfilled appears to be zero in the LSHRLI, as all the plastic wastes are either recycled or incinerated with energy recovery. Therefore, taking into consideration the amount of plastic waste landfilled, LSHRLI gives the best results.

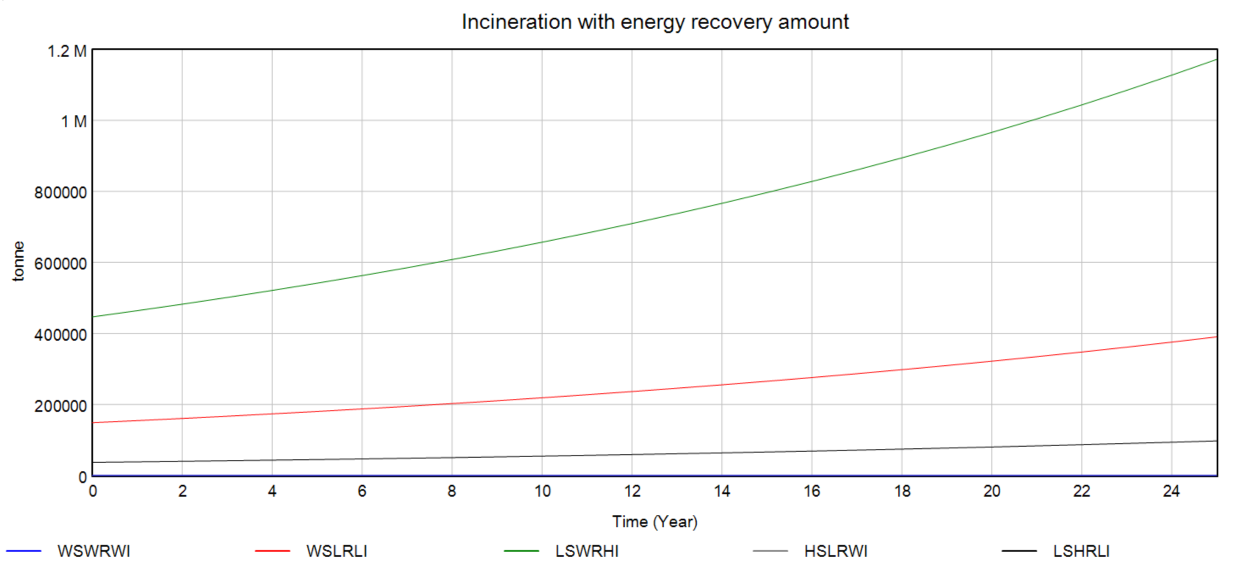

Figure 5. Incineration with energy recovery amount for five scenarios

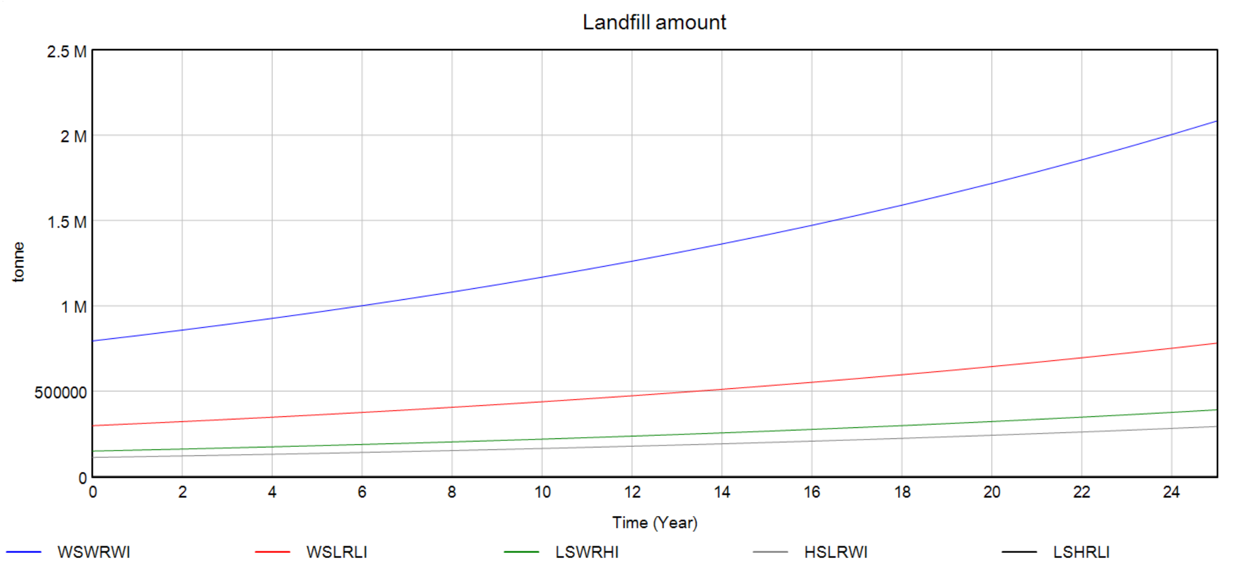

Figure 6. Landfill amount for five scenarios

Figure 7 presents the results from the simulation of the five scenarios regarding net GHG reduction amount. The amount of net GHG reduction amount is at its highest throughout the 25 years in LSWRHI, reaching 2,184,320 $MTCO_2E$. Since incineration with energy recovery technology leads to the highest amount of GHG emission reduction, the high percentage in this scenario (75%) has led to the high amount of GHG reduction. LSHRLI has also resulted in a high amount of GHG reduction, which is 6.83% lower than the amount in LSWRHI. Additionally, the amount of net GHG reduction in HSLRWI is slightly less than the amount in LSHRLI, with a percentage of 6.55%. In WSLRLI, the amount of GHG reduction is lower than the amount in HSLRWI with a percentage of 41.20%. However, the amount of net GHG reduction appears to be zero in WSWRWI, as all the plastic waste ends up in landfill. Disposing plastic wastes in landfill doesn't cause any decrease in the total GHG emission amount. Therefore, LSWRHI gives the best results in terms of the net GHG reduction amount.

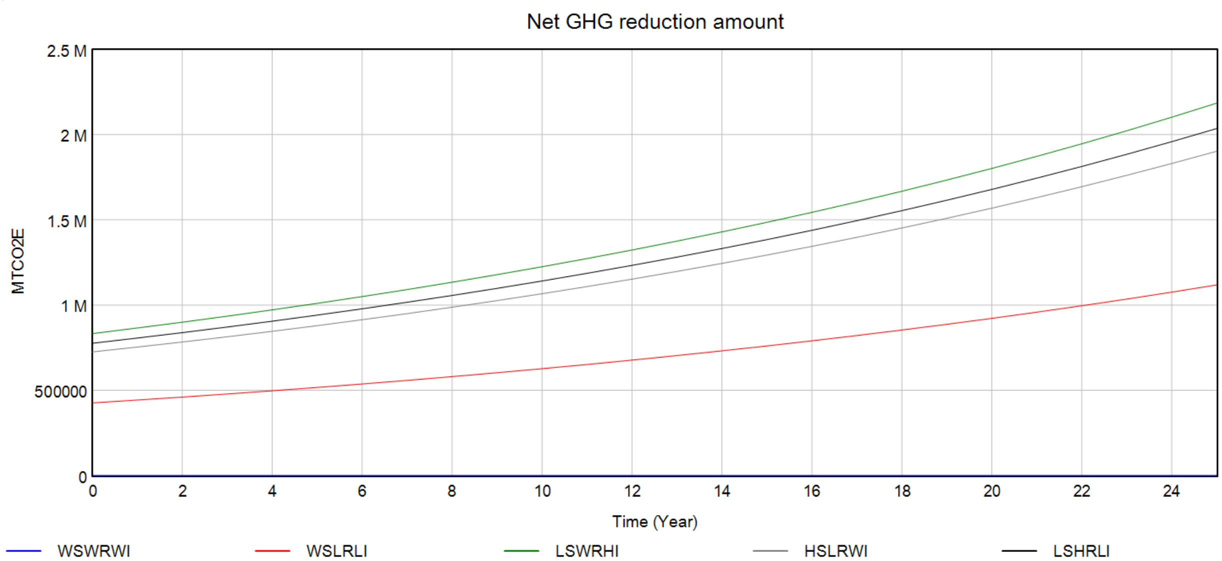

Figure 7. Net GHG reduction amount for five scenarios

4.2. Model Validation

Model validation is an important part of every model-based methodology including system dynamics. It is described as creating confidence in the effectiveness of a model in achieving its objective. After identifying the required variables and equations, number of tests should be conducted to achieve the building confidence in the model (Sterman 2000). The proposed SD model was subjected to structural validation, which was evaluated through performing (1) structure verification test, (2) dimensional consistency test, and (3) extreme condition test.

Structure verification test was conducted using two methods. First, by answering several questions proposed by Sterman (2000) to evaluate the model. The questions were all qualitatively answered either by researchers or by interviewees involved in the study, such as leaders or managers of MSPW management system. Second, through comparing the proposed system to existing knowledge from the literature.

In addition, the dimensional consistent test was conducted through reviewing the mathematical units utilized in each equation of the model. This was done by checking if the dimension on the equation's left side was equivalent to the dimension of the right side.

Furthermore, to conduct the extreme condition test, three extreme values, 0, 50%, and 100%, were assigned to three selected parameters, which are source separation percentage, recycling percentage of unseparated recyclable plastic waste, and incineration with energy recovery percentage. Three different scenarios were designed for the model's validation: Scenario A (source separation percentage = 0, recycling percentage of unseparated recyclable plastic waste = 100%, and the incineration with energy recovery percentage = 0), scenario B (source separation percentage = 100%, recycling percentage of unseparated recyclable plastic waste = 0, and the incineration with energy recovery percentage = 0), and scenario C (source separation percentage = 50%, recycling percentage of unseparated recyclable plastic waste = 50%, and the incineration with energy recovery percentage = 0).

At the end of the 25 years, scenario A shows that the accumulated amount of source separated plastic waste recycled will be 0. It also shows that the accumulated amount of unseparated plastic waste recycled will be 2,082,530 tonnes and the accumulated amount sent to landfills is 0. In scenario B, there is a 100% increase in the accumulated amount of source separated recycled plastic waste, reaching 2,082,530 tonnes. There is also a 100% decrease in the accumulated amount of unseparated plastic waste recycled and the accumulated amount sent to landfills is still 0. However, in scenario C, the accumulated amount of source separated recycled plastic waste is decreased by 50% compared to scenario B, reaching 1,041,260 tonnes. The accumulated amount of unseparated plastic waste recycled in scenario C (520,632 tonnes) is increased by 100% compared to scenario B and decreased by 75% compared to scenario A. Furthermore, the accumulated amount sent to landfills in scenario C (260,316 tonnes) is increased by

100% compared to both scenarios, A and B. The extreme condition test clearly shows the consistency of the variables and how the relationship among them is coherent. Therefore, all the tests performed proved the structural validity of the proposed model.

5. Conclusion
Developing a sustainable MSPW management system, through the application of waste measures and policies, is important for future sustainable development. Therefore, this study aims to evaluate the impact of multiple sustainable waste measures and policies on MSPW management and GHG reduction amount. To achieve this goal, a generic SD model is developed by integrating three waste measures, namely source separation policy, recycling process, and incineration with energy recovery technology in the MSPW management system. Vensim® software is used to develop the proposed SD model. To test the impacts of these sustainable measures, five different scenarios are conducted taking into account different implementation levels for the three measures. The simulation results indicated that scenarios HSLRWI and LSHRLI perform best in terms of the amount of plastic waste recycled, scenario LSWRHI leads to the highest amount of GHG reduction, and scenario LSHRLI gives the highest amount of incinerated plastic waste with energy recovery and least amount of plastic waste landfilled. Therefore, the proposed model helps decision makers in choosing the scenario that works best according to their strategies and goals.

For future studies, other waste management measures, such as plastic reduction policy, are planned to be tested. The economic impact of integrating sustainable waste measures and policies may also be studied in the future. In addition, it is anticipated to apply the proposed generic SD model to other cities to help them evaluate the impact of multiple measures and policies on their MSPW management.

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