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Material flow analysis and life cycle assessment of solid waste management in urban green areas, Thailand

Indika Thushari¹, Juckrit Vicheanteab¹ and Dao Janjaroen^{1,2*} 

Abstract

This study presents solid waste management planning in an urban green area, Bangkok, Thailand based on the material flow analysis (MFA) and life cycle assessment (LCA). Global warming potential (GWP) of four scenarios for handling solid waste generated in Chulalongkorn University Centenary Park, 2018 was assessed concerning the different ratios of waste recycling, composting, incineration, and landfilling. The results show that alternative systems proposed will result in lower GWP than the existing waste management strategy. The MFA results reveal that the final weights of solid waste ending up in a landfill are 98.8, 101.9, 68.2, and 44.8 t yr⁻¹ for scenarios 1, 2, 3, and 4, respectively. Increased rates of landfill diversion by increased recycling, composting, and incineration decreased the quantity of solid waste disposed to the landfill and improved the environmental profile of the park waste management system. The LCA results found landfilling to be the dominant source of greenhouse gas (GHG) burdens, while waste recycling was found to result in the reduction of GHG. The results highlight that the use of MFA and LCA as a combined tool to evaluate the environmental performance of solid waste management systems provides valuable information for policy and decision-makers.

Keywords: Solid waste management, Global warming potential, Urban green areas, Material flow analysis, Life cycle assessment

Introduction

Municipal solid waste (MSW) management is a critical issue in Thailand. In 2015, Thailand generated 26.9 Mt of MSW national wide, 16% of which was generated alone in the country's capital, Bangkok. Even though the composition varies due to urbanization, population density, and income in different areas, the MSW in Thailand typically consists of about 51% of green/organic waste, 22% of plastic, 13% of paper, and 3% of glass. Pollution Control Department (PCD) has stated that 54% of collected waste in Thailand is properly disposed of, while the rest is incorrectly disposed of as open burning or illegal burning. The absence of an effective

integrated waste management system in the country creates many environmental, economic, and social problems [1, 2]. Figure S1 in Supplemental Material depicts the current waste management practices in Thailand.

The waste management sector in any country is under increasing pressure to improve its environmental performance [3]. Solid waste management (SWM) is often a local responsibility in most countries. Limited resources and the capacity in local authorities as well as poor implementation of targeted legislation challenge sustainable waste management practices in low- and middle-income countries compared to that in higher-income countries. Therefore, higher-income countries precede towards sustainable waste management practices. Source reduction is the most favored waste management practice from the sustainable waste management hierarchy. Higher-income countries have achieved a higher level of

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progress in waste reduction as well as advanced recycling practices even though the rate of waste generation is higher than that in low and middle-income countries [2–4]. Efficient waste separation at the source makes composting/anaerobic digestion, and incineration is easier and effective. The practice of composting in low- and mid-income countries is less popular despite the high organic content in MSW due to contamination and the operating cost of the large plants. Advancing waste incineration with environment controllers and energy recovery systems are widely used in high-income countries with low-land availability [2–4]. However, globally most MSW is openly dumped or disposed of to a landfill (Fig. S1) [4]. In general, SWM contributes to 5% of global greenhouse gas (GHG) emissions [4]. Global warming and climate change due to an increased level of GHG is a serious global concern. Therefore, sustainable MSW management is a crucial aspect that should be addressed in an integrated approach in Thailand as a leading country in developing Asia. The most popular waste disposal method in Thailand is landfilling [1, 2]. Landfilling has many negative environmental impacts. This practice contributes to climate change on a global scale due to the emission of a large amount of GHG from the degradation of organic materials. Besides landfilling, incineration and composting are other popular, yet less used methods of MSW management in Thailand [2]. Waste recycling shows a significant contribution to GHG mitigation due to the possible substitution of virgin material production, thus considered as a sustainable waste management option [5]. Therefore, the improvement of SWM systems in terms of recovering values in the form of materials and energy would enhance resource efficiency and GHG mitigation potentials [5].

Urban green areas are becoming increasingly important due to the increased rate of urbanization, and their role in maintaining a healthy population and economy in any developed or developing city [6, 7], such as Bangkok, Thailand. Maintenance and user activities in these urban green parks generate a considerable amount of solid wastes which ends up as a major contributor to the increasing generation of MSW [8]. Therefore, the assessment of potential treatment methods of such waste is important in policy and decision-making initiatives. Shi et al. [9] and Raud et al. [10] have reported the utilization potential of lignocellulose waste generated in urban parks for biofuel production in China and Estonia, respectively. However, environmental assessments of the treatment of garden wastes are reported only in a few studies in the literature [8, 11]. The Chulalongkorn University Centenary Park (CUCP) is a recently built multi-purpose urban forest that serves as a quality green space for the residents of the surrounding community. Many organized public activities

and the increasing number of visitors in the park contribute to a considerable amount of solid waste generation. This heightens the necessity of sustainable waste management for the park.

Integrated material flow analysis (MFA) and life cycle assessment (LCA) has become an increasingly recommended method for decision making in SWM systems. MFA on the levels of goods helps in understanding the functioning of processes and connection between processes in waste management by acting as an excellent tool for analyzing, and managing flows of wastes, secondary products, and residues [12]. LCA evaluates environmental benefits and burdens associated with waste management systems. LCA analyses system performance and allows comparison of alternatives while enabling the identification of possible system improvements [13]. Table 1 presents an overview of recent applications of MFA and LCA as a tool to support waste management decision making. Turner et al. [3] (environmental performance of MSW system in Wales); Sevigne-Itoiz et al. [14] (Spanish paper and cardboard recycling system); Nakem et al. [15] (Polyvinyl chloride waste management in Thailand); Padeyanda et al. [16] (food waste management in Daejeon Metropolitan City in Korea); Haupt et al. [17] (environmental performance of MSW management in Switzerland in 2012); demonstrated the use of complementary methodologies of MFA and LCA in combination to assess the environmental performance of waste management systems. Nevertheless, the use of MFA and LCA as an integrated assessment tool for MSW management in Thailand is almost non-existing in the literature. Therefore, environmental assessments of SWM should be based on the flows described by MFA and quantified using LCA, because such assessments provide valuable and transparent information for decision making.

Strong waste management policies that guide local actions promote sustainable waste management practices. Information on the current status of waste generation patterns and evaluation of available management systems are critical in revising and implementing policies. Also, this directs local governments to select appropriate management practices for future demand. Therefore, systematic evaluation of SWM in the CUCP is necessary to identify and overcome the shortcomings of the current practice. Thus, the main focus of the present study is to quantify the mass balances of the solid waste in CUCP, Bangkok, Thailand, and secondly to provide an environmental evaluation of a range of waste management options with regards to GHG emissions/Global Warming Potential (GWP). Identification of the contribution of waste streams and the treatment process for GWP will support decision and policy making practice in the local waste management sector in Thailand.

Table 1 Application of MFA and LCA on waste management

Application	Waste type	Geographical scope	Functional unit	Impact coverage	Conclusions	Ref.
MFA /LCA	MSW	the city of Cardiff, Wales	Management of 168,526 t of MSW in Cardiff, collected between April 2012 and March 2013	GHG	- Evaluate a complex, multi waste stream at the meso- level. - Demonstrates the use of complementary methodologies of MFA and LCA in combination to provide valuable information about the environmental performance of a SWM system.	[3]
MFA/consequential LCA	Waste paper and cardboard	Spain	Recycling of 1 t of waste paper collected in Spain (Nationally and internationally)	GHG	- The future GHG quantifications should be based on the flows described by MFA and quantified using consequential LCA because methodologies that accurately account for GHG are necessary for decision-making.	[14]
MFA/LCA	Polyvinyl chloride (PVC)waste	Thailand	Management of post-consumer PVC waste generated during 2013–2014	GWP, Energy use	- MFA successful estimated PVC waste flows while LCA evaluated environmental impacts of PVC waste management	[15]
MFA/LCA	Food waste	Daejeon Metropolitan City in Korea.	Management of 1 t of food waste generated from households and small-scale restaurants	GWP, Acidification potential, Eutrophication potential, and photochemical ozone creation potential	- MFA and LCA were used to quantify the potential environmental impacts of food waste management.	[16]
MFA/LCA	MSW	Switzerland	Treatment of all MSW generated in Switzerland, 2012.	Cumulative exergy demand climate change, human toxicity and ecotoxicity	- The modular MFA/LCA design allows for a detailed assessment of recycling and thermal treatment pathways as well as national waste management strategies.	[17]

Methodology

Goal and scope definition

The CUCP is located in the center of Bangkok, Thailand, providing a quality green space for the surrounding communities. Figure S2 shows the location of the CUCP. The park plays a vital role in addressing some major environmental issues, such as water management and urban heat island effect in a rapidly developing city with climate change vulnerability [18]. An increasing number of visitors, as well as many activities organized in the park and the contiguous communities, generate a substantial amount of solid waste per day.

The main goal of the study is two-fold: to quantify the mass balance of the existing SWM system, and to quantitatively evaluate the GWP of current SWM and potential alternative systems.

Sampling was done twice a day (day and night time), 2 days a week (weekday and weekend day) throughout 2018, to quantify solid waste generation in the park. Waste collected from the publicly available waste bins and the garden was sorted and weighed at the site. A combination of methodologies, such as MFA and LCA was applied to assess the current SWM system and the possible alternative systems including national policy targets. MFA is a systematic assessment of flows and stocks of materials within an arbitrarily complex system defined in space and time [19]. Mass flows and the stocks of the waste management systems were calculated using MFA. The environmental impacts of the defined waste management systems were assessed using LCA. The assessment followed the ISO 14040 and 14,044 standards for LCA [20, 21].

System boundaries and scenarios

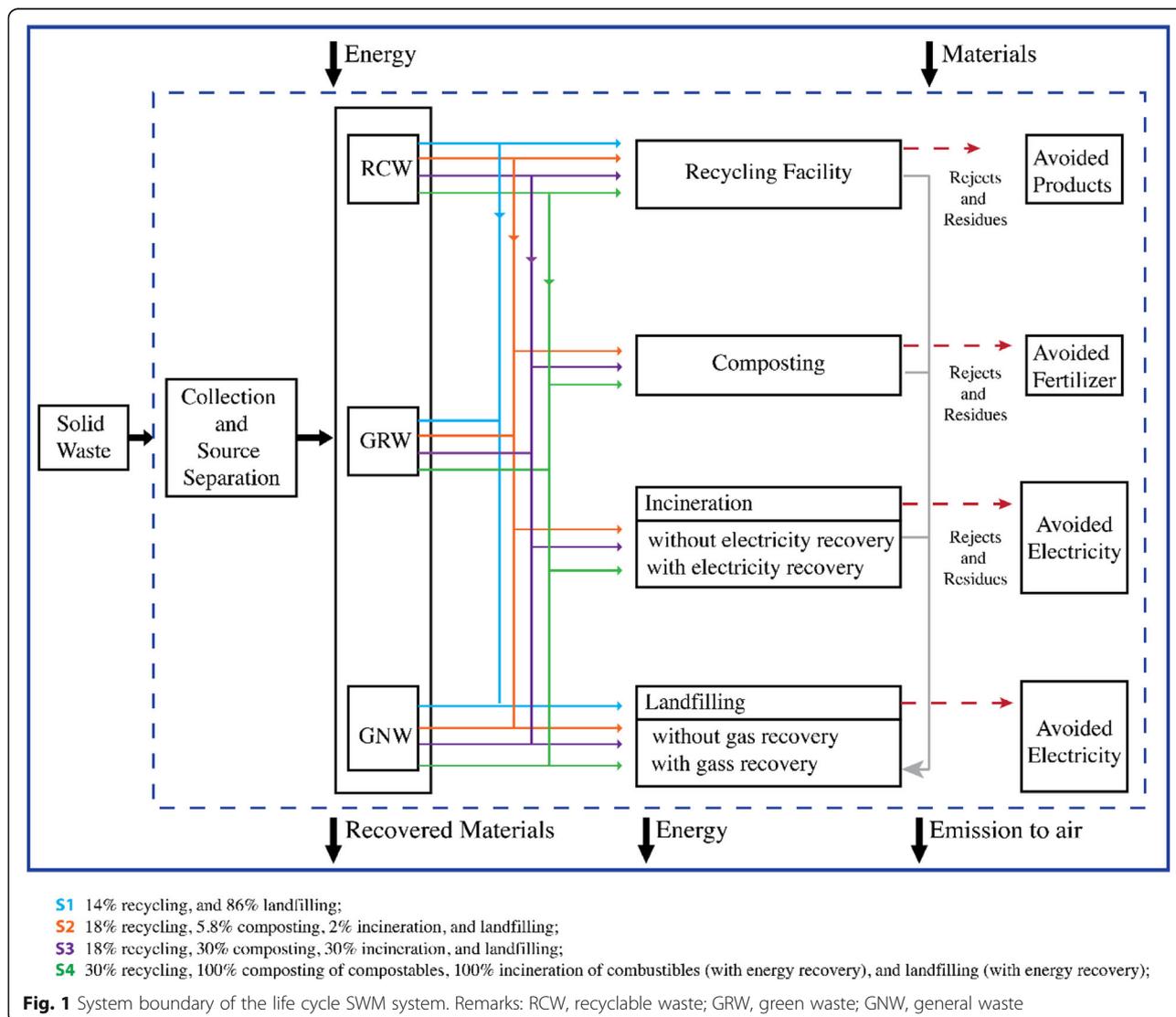
The functional unit (FU) was defined as the management of 112.4 t of solid waste collected in the CUCP in 2018. The SWM system comprised a foreground system and background system. The foreground system directly involved with the reference flow management and the background system linked with the foreground system included energy production and avoided materials.

All the activities required managing the waste from their point of collection and onsite sorting, transportation, treatment, and final disposal were assessed to evaluate the waste management system comprehensively. The ‘zero burden assumption’ was made, whereby the environmental impacts from the upstream life cycle stages before the waste collection were not included [3, 22]. Only the direct consequences of waste management in selected scenarios were considered. Environmental impacts of the infrastructures and capital goods and

wastewater from the treatment plants were also excluded similar to assumptions made by [3, 8, 23]. This is because they were less important to the overall results of scenario comparison. This allows the comparison of the many scenarios in a simple way [8].

System boundaries of the SWM system were defined according to cradle to grave principle and are presented in Fig. 1. Four scenarios for handling and treating the generated park waste were compared in the study.

S1 (scenario 1) represents the most common and simplified SWM system, which involves total recycling of all recyclable wastes, such as plastic, glass, paper, and aluminium/steel cans, and disposal of the rejects and the rest of the garden waste directly to a conventional landfill. According to the solid waste composition of the park, 86% solid waste (garden waste and general waste) for landfill disposal, and the rest of 14% for recycling (25% plastics, 48% glass, 16.7% paper, and 9% aluminium) were considered.



S2 (scenario 2) represents the current MSW management practice according to the State of Pollution Report 2015, Thailand [1]. S2 considers 18% of solid waste being sent for recycling, 5.8% for composting (21% from recycled waste, 2% from other residual organic and garden waste), 2% for waste to energy incineration plant, and the rest from general, residual, and green waste to a conventional landfill.

S3 (Scenario 3) represents a combination of an increased ratio of composting (30%), and incineration (30%). About 30% of the organic wastes are sent to a composting plant, while 30% of recycling rejects and combustibles are sent to incineration plants. The remaining waste and the residuals from composting and incineration are sent to a conventional landfill.

The national policy plan target is to increase recycling up to 30% and to achieve 100% proper SWM by 2030. S4 (scenario 4), based on the national policy plan, Thailand for 2017–2030 [24], considered 30% recycling of generated waste (including 100% recycling of dry recyclables), 100% composting of organic waste and incineration of combustibles, and the use of proper sanitary landfill management (with 50% gas collection) for the rest of the solid waste and residues.

Impact coverage

Climate change is an urgent global environmental issue with increasing significance [25]. Climate change has been recognized as one of the good representatives for the environmental impact of SWM [3]. Kaza et al. [4] stated that more than 80 countries have identified SWM as an intervention area in mitigation and adaptation to climate change under the United Nations Framework Convention on Climate Change Agreement. Several studies have shown a significant reduction of GHG emissions through attempts to formalize waste management [4, 26]. Therefore, climate change in terms of GWP is considered as the only impact coverage in this study.

Life cycle inventory

Data for the life cycle inventory were gathered from various primary and secondary sources including reports, literature, and the Ecoinvent 3 databases as detailed below. Also, all the assumptions made are summarized in Table 2.

Reference flow characterization

A static MFA approach was applied and the freeware STAN 2.6, developed at the Vienna University of

Table 2 Assumptions used in MFA and LCA

Assumption	Ref.		
Goal and scope	<ul style="list-style-type: none"> - Environmental impacts from upstream life cycle stages before the SW collection were excluded - Environmental impacts of the infrastructures, capital goods, and wastewater treatment from the treatment plants were also excluded - The collection and the source separation assumed to have no material and energy consumption 	[3, 8, 23]	
LCI	MFA	<ul style="list-style-type: none"> Considered transfer coefficients are recycling process (25.5%-plastic, 11%-paper, 0%-glass, 16.5%-aluminum), 35%-composting process, and 17%-incineration process 	[24, 27, 28]
		<ul style="list-style-type: none"> - Emissions of biogenic CO₂ were assumed to be neutral 	[27, 29]
	Landfilling with gas recovery	<ul style="list-style-type: none"> - The efficiency of the landfilling system with gas recovery is 50% 	[27, 29]
	Recycling system	<ul style="list-style-type: none"> - Secondary products produced from the recycling process replace the production of alternative products. The potential avoidance of primary products (90%-plastic, 95%-glass, 90%-paper, 75%-aluminum) 	[30, 31]
	Composting process	<ul style="list-style-type: none"> - Compost produced from the composting process replaces the chemical fertilizers in S4. The potential avoidance of chemical fertilizer usage is 7.1 kg N, 4.1 kg P₂O₅, 5.4 kg K₂O t⁻¹ of compost. 	[30, 31]
	Incineration process	<ul style="list-style-type: none"> - The electricity recovering efficiency at the incineration plant for S2 and S3 is 8% and for S4 20% - Electricity produced from incineration displaces an equivalent amount of electricity generated 	
Transportation	<ul style="list-style-type: none"> - Transport distances 50 km (to landfill) 10 km (to composting plant) 100 km (to incineration plant) 50 km (to recyclable waste collection plant) - the process "Transport, municipal waste collection, 21 t lorry and freight, lorry" for waste transportation to the landfill site, composting plant, and incineration plant - the process "Transport, freight, lorry, unspecified" was selected for the transportation of recyclable waste to the treatment facility 		

Technology, was used to set up the mass flows of the different scenarios [19]. The input (import flows) into the waste management system is the solid waste generated and collected in the CUCP in 2018. The outputs (export flows) are the secondary products and emissions to the environment. Transfer coefficients describe the partitioning of a material or a substance in a process [32]. Therefore, outputs were calculated mainly using transfer coefficients which were derived based on our data and by the literature search. Landfills are final sinks where all the remaining solid waste arrives finally for long term storage. The waste that has not been properly treated and also residues from other treatment facilities end up in landfills. Therefore, they are the only stocks used in this system.

Transportation and electricity

After the collection of waste generated at the CUCP, segregated wastes were transported into treatment plants and the landfill. Transportation and pre-treatment operations contribute to a part of the environmental impacts causing global warming. Transport distances between the park to the landfill site, a composting plant, incineration plant, and the recyclable waste collection plants were considered as 50, 10, 100, and 50 km, respectively. The unit process for the transportation (SimaPro 8.5.0) was selected as the process 'Transport, municipal waste collection, 21 metric ton lorry' for waste transportation to the landfill site, composting plant, and incineration plant while 'Transport, freight, lorry, unspecified' was selected for the transport of recyclable waste to the treatment facility as they are transported by local collectors. All electricity requirements are derived from Thailand's national electricity records and used as medium voltage under the electricity country mix as reported in SimaPro 8.5.0.

Landfilling

Landfilling is the most common municipal waste disposal method in Thailand. A conventional landfilling system without energy recovery was considered for S1 to S3, while in S4 a landfilling system with 50% CH₄ recovery was considered. Among landfill gasses, CH₄ contributes to GWP potential whereas CO₂ is of biogenic origin [33]. CH₄ emissions from uncontrolled landfilling have been considered as the third largest anthropogenic CH₄ source [34]. In this study, CH₄ generated in the landfilling system is estimated based on the IPCC (Intergovernmental Panel on climate change), 2006 default method [30, 33] using Eq. (1).

$$\begin{aligned} \text{CH}_4 \text{ emission (Ggyr}^{-1}\text{)} \\ = \left(\text{MSW}_T \times \text{MSW}_F \times \text{MCF} \times \text{DOC} \times \text{DOC}_F \times F \times \frac{16}{12} - R \right) \times (1 - \text{OX}) \end{aligned} \quad (1)$$

where MSW_T is the total solid waste generated (Gg yr⁻¹), MSW_F is the fraction of solid waste disposed, MCF is the methane correction factor, DOC is the degradable organic carbon, DOC_F is the fraction of DOC factor, F is the CH₄ fraction, R is the CH₄ recovered (Gg yr⁻¹), and OX is the oxidation factor.

The efficiency of the landfilling system with gas recovery was assumed to be 50% [27] in S4. Details of energy and material inputs for the landfilling system are presented in Table 3.

Recycling

A recycling system for mixed plastic, mixed container glass, paper, and aluminium/steel cans was considered. GHG emissions from each type of recyclable and virgin resources were calculated based on the country-specific information in Thailand as reported by [31] and Ecoinvent 3 databases [36]. GHG avoidance potential for each recyclable material was considered and used since the amount of recovered materials is equal to the amount of potential avoidance of virgin resources [31]. Table 3 presents the energy and material inputs for the wastes recycling facility. The information regarding the avoided virgin materials due to waste recycling is presented in Table 4.

Composting

Since the majority of the waste collected in the park is organic and due to Chulalongkorn University's recent aspiration towards composting of organic waste generated at the University, this treatment method was considered for S2, S3, and S4. The data, such as diesel and electricity requirements during the operation phase of composting, were taken as the windrow composting of the commingled waste facility in Wiang Fang municipality, Northern Thailand as reported by Chanchampee [35]. Emissions during the operation were estimated according to IPCC, 2006 default emission factors [33]. CH₄ formed due to anaerobic degradation of waste was taken into account, while CO₂ was ignored since such CO₂ has biogenic origin [33]. The details of inputs of the inventory of the composting system are shown in Table 3. The potential avoidance of chemical fertilizer usage (7.1 kg N, 4.1 kg P₂O₅, 5.4 kg K₂O t⁻¹ of compost), and respective emissions were considered for S4 [31].

Incineration

Incineration is considered to be an effective treatment method that can decrease the volume (90%) and the mass (75%) of waste to be landfilled [37]. This waste treatment generates global warming-related emissions, such as CO₂, N₂O, and NO_x [33]. Incineration was used for S2, S3, and S4. The inventories of incineration for operation including total fossil fuel and electricity

Table 3 Inventories for landfilling, recycling, composting, and incineration facilities

Resources Input	Value	Unit	Ref.
Landfilling			
Electricity	2.5	kWh t ⁻¹	[35]
Electricity demand for gas collection	0.2	kWh m ⁻³ landfill gas	[35]
Diesel	0.6	L t ⁻¹	[35]
Recycling			
Plastics			[36]
Electricity	544.2	kWh t ⁻¹	
Glass			[31]
Coal brown	2.1	kg t ⁻¹	
Natural gas	20.9	m ³ t ⁻¹	
Coal	10.3	kg t ⁻¹	
Limestone	4.5	kg t ⁻¹	
Sodium chloride	0.6	kg t ⁻¹	
Paper			[31]
Electricity	436.7	kWh t ⁻¹	
Kaolin	53.5	kg t ⁻¹	
Aluminium sulphate powder	8.6	kg t ⁻¹	
Aluminium			[31]
Electricity	89.1	kWh t ⁻¹	
Total Thermal Energy	3328.6	MJ	
Bauxite	0.1	kg t ⁻¹	
Cast ingot	700	kg t ⁻¹	
Composting			
Electricity	5.6	kWh t ⁻¹	Wiang Fang plant, Chiang Rai, Thailand [35]
Diesel	1.3	L t ⁻¹	
Incineration			
Electricity	86.4	kWh t ⁻¹	Phuket incineration plant [37]
Diesel	0.4	kg t ⁻¹	
NaOH	0.03	kg t ⁻¹	
Lime	6.5	kg t ⁻¹	
Water	356	kg t ⁻¹	

Table 4 Substitution options for recycling

Type of recyclables	Avoided production	Ratio (%)	Ref.
Mixed plastic waste	Polyethylene terephthalate	90	[31]
Mixed glass waste	White glass	36	[31]
	Green glass	57	
	Brown glass	02	
Mixed paper waste	Kraft paper	90	[31]
Aluminium waste	Aluminium	75	[31]

consumption and other material used were obtained from the Phuket incineration plant, Thailand as reported by Menikpura et al. [38] and Chanchampee [35], and are presented in Table 3. According to Menikpura et al. [38], the average electricity production potential in the Phuket incineration plant is 144 kWh t⁻¹ combustibles, while the operation activities require 60% of the produced electricity. The electricity recovering efficiency at the incineration plant for S2 and S3 was considered as 8%, while 20% is considered for S4. However, only the combustion CO₂ emissions from the fossil-based waste were considered and GHG emissions were estimated according to IPCC, 2006 Tier 2 approach [33] using Eq. (2).

$$CE = \sum_i (SW_i \times dm_i \times CF_i \times FCF_i \times OF_i) \times \frac{44}{12} \tag{2}$$

where CE is the combustion emissions (kg CO₂ t⁻¹ of waste), SW_i is the total amount of solid waste type i (wet weight) incinerated (kg t⁻¹ of waste), dm_i is the dry matter content in the waste incinerated, CF_i is the fraction of carbon in the dry matter, FCF_i is the fraction of fossil carbon in the total carbon, OF_i is the oxidation factor, 44/12 is the conversion factor from C to CO₂, and subscript i is the type of fossil-based waste incinerated.

Life cycle impact assessment

The life cycle impact assessment was performed in terms of GWP using the IPCC 2013 GWP 100a method [25]. The considered GHGs were CO₂-fossil, CH₄, and N₂O. GWP is expressed as kg CO₂e.

Sensitivity analysis

The sensitivity of the results of the impact of GWP of considered SWM systems was investigated. The sensitivity analysis 1 was performed in S4, varying the electricity recovery efficiency (8–30%) of the incineration plant. This evaluates how results are sensitive to variations in input data and modeling choices [39]. The sensitivity analysis 2 was performed by changing the impact assessment method for S1–4. IPCC 2013 method [25] measures only the impact regarding climate change as a mid-point indicator while the ReCiPe method measures a broader set of environmental impacts [40]. ReCiPe method is considered as one of the most popular and widely used methods to investigate GWP. It was

developed integrating two impact assessment methods; the problem-oriented approach and the damage-oriented approach [41]. Therefore, the ReCiPe Midpoint (H) method was used to check the robustness of the results obtained from the IPCC 2013 GWP 100a. The GWP is sensitive to the selected time horizon. Thus, two fixed time horizons were selected (20 and 100 yr) as the GWP of 20-yr time horizon is higher than that of the 100-yr time horizon.

Results and discussion

Characterization of solid waste

The total input of solid waste into the investigated system is 112.5 t in 2018. Figure 2 presents the generated solid waste composition in the CUCP. Garden waste is the major constituent of the organic waste generated in the park representing 81% of the total waste. The rest includes recyclable waste: 7% glass, 4% plastic, 1% aluminum/steel, and 2% potentially recyclable paper waste. The general waste (5%) includes food waste, and hygiene products, such as diapers, clothes, and other wastes.

MFA as a base for decision making

Since the overall set of data in MFA allows comparing the scenarios and quantifying the wastes loaded to each treatment method, MFA was developed for each of the considered scenarios. The MFA on the level of goods and the details of inputs, outputs, and stocks in ton per year for S1, S2, S3, and S4 are presented in Fig. 3a, b, c, and d, respectively. The treatment methods, substitution options, and the quantity of solid waste distributed in different scenarios are also presented in Tables 5, 6, 7.

Figure 3a presents the mass balances of waste management in S1. 112.5 t yr⁻¹ of solid waste generated in the

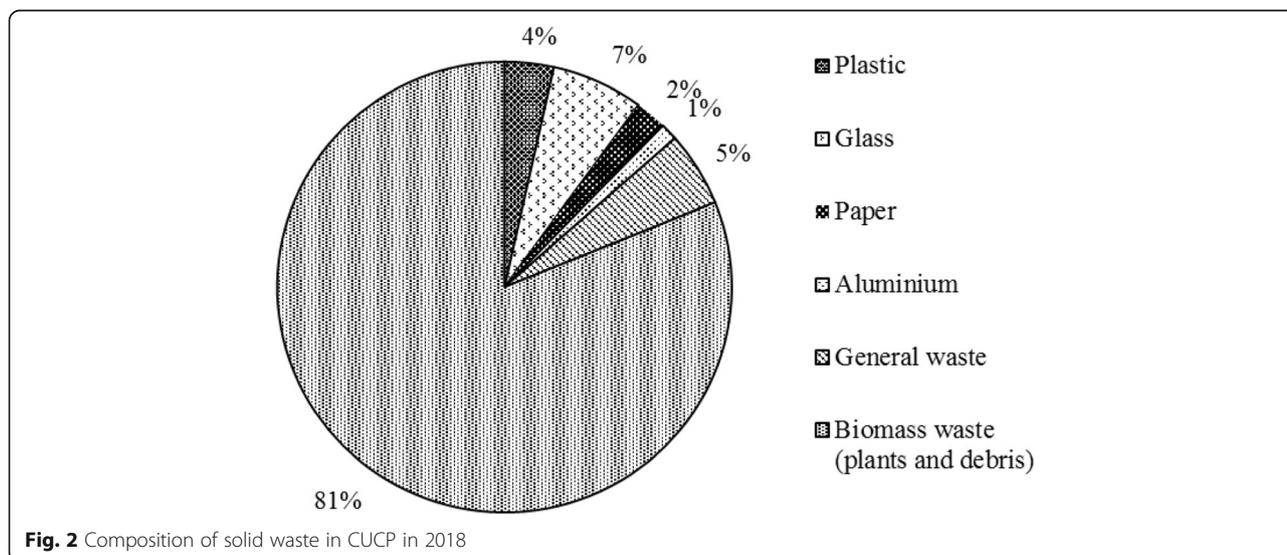


Fig. 2 Composition of solid waste in CUCP in 2018

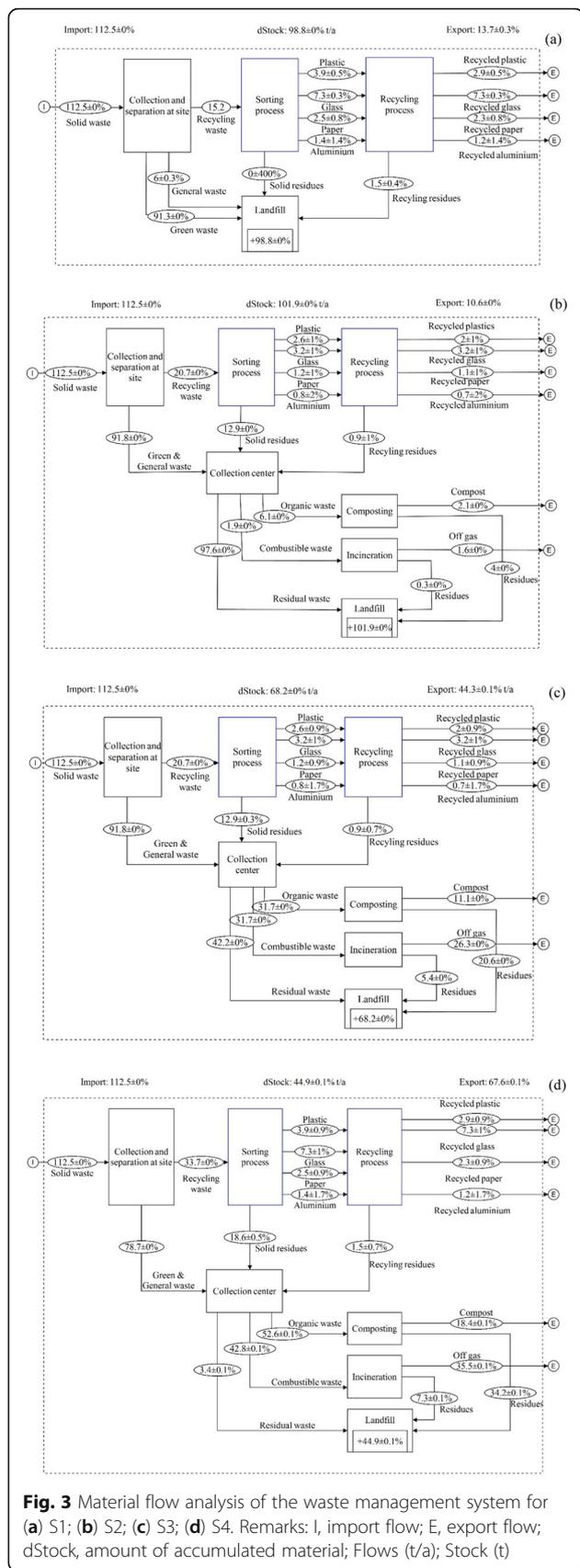


Fig. 3 Material flow analysis of the waste management system for (a) S1; (b) S2; (c) S3; (d) S4. Remarks: I, import flow; E, export flow; dStock, amount of accumulated material; Flows (t/a); Stock (t)

park were collected from the municipality, 86% of which were transported to a landfill, while the rest as recyclable wastes (13.5%) were transported to recycling facilities. The dominant primary waste stream of the park is green/garden waste (91.3 t yr^{-1}). The model suggests that 13.7 t yr^{-1} treated recyclable wastes can be directly used as substitutions of respective raw materials if 100% of the recyclable wastes were properly treated.

Compared to S1, S2 was found to have a decreased ratio of recycling and an increase in the amount of solid waste transported to a landfill as a result of residuals from composting and incineration facilities. As can be seen in Fig. 3b and Table 5, more than 90% of the carbon ends up in a landfill in S2. This increased amount of carbon increases the amount of landfill gas, contributing to global warming. Also, this decreases the potential benefits of the ability of material and/or energy recovery from certain wastes. Therefore, it is clear that the current municipal waste management system in Thailand should be improved in a way that decreases the volume of a landfill and increases the ratio of material and energy recovery from wastes.

The combination of an increased ratio of wastes going to composting and incineration facilities in scenario S3 and S4 decreases the amounts of waste that end up in a landfill (Fig. 3c, and d). Landfill diversion ratios of S3 and S4 are found to be 63 and 98%, respectively. Composting of organic waste and incineration of combustibles in S3 and S4 decreases the amount of direct solid waste disposal (63.4 and 95.4 t yr^{-1} , respectively) over the landfill, decreasing the potential long-term emissions to the environment. Besides, enhanced composting and incineration approaches, together with the considered increased energy and material recovery ratios of S4, balance the possible environmental burdens caused in S2 and S3.

Two different ratios of recycling were considered in the recycling system. Figure 4 indicates the mass balances of recycling systems. In S1 and S4, 100% of collected recyclables were considered recycled despite the current waste management system in Thailand, while S2 and S3 followed the current system as reported by PCD, 2016 [1] as shown in Table 7. The recyclables are manually sorted and weighted at the site of the waste collection before transported into the treatment facility. Therefore, it was assumed that the residues are negligible at the sorting facility. Similar to the recycling ratio, the recycling processes have different efficiencies. Therefore, recycling residues amounts in waste flow are different [28]. Transfer coefficients for the recycling processes of plastic, glass, paper, and aluminium were taken from Arena and Di Gregorio [28] and the respective ratios of recycling residues are presented in Table 7.

Table 5 Comparison of MFA indicator results for different scenarios

SWM system	Description ^a	Quantity of solid waste treated			
		S1	S2	S3	S4
Landfilling (t yr ⁻¹)		98.8	101.9	68.2	–
Landfilling with energy recovery (t yr ⁻¹)		–	–	–	44.8
Recycling (t yr ⁻¹)		15.2	7.8	7.8	15.2
Composting (t yr ⁻¹)		0	6.1	31.7	52.6
Incineration with energy recovery (t yr ⁻¹)		0	2.0	31.7	42.8
Landfill ratio (%)	Total tons of SW sent directly to the landfill plus tons of rejected from other facilities divided by total tons of SW	87.8	90.6	60.6	39.8
Recycling/composting ratio (%)	Sum of tons of SW sent for recycling and composting divided by the total tons of SW	13.5	12.4	35.0	60.3
Landfill diversion ratio (%)	Sum of tons of SW not sent directly to landfill divided by total tons of SW	13.5	14.3	63.3	98.3

^a Description and the calculations are according to Turner et al. [3]

It was assumed that the efficiency of the composting facility is 35%, and 0.35 t of compost can be produced from 1 t of organic waste input. In addition, it was considered that incineration of 1 t of combustible wastes generated 0.17 t of residues which should end up in a landfill [35].

Landfills became a final sink for solid waste in all S1, S2, S3, and S4 scenarios. A final sink holds a substance for a very long period or destroys substances completely [42]. Increased ratio of alternative waste treatments in S3 and S4 decreases the amount of un-treated and residual waste, minimizing the use of a landfill. It was found that, from S2 to S3 and S4, the landfilling ratio decreased from 90 to 60 and 39%, while the landfill diversion ratio increased from 14 to 63 and 98%, respectively, due to the increased ratio of recycling/composting and incineration (Table 5). This provides various benefits to the waste management system.

Carbon is an indicator of resource potentials, such as energy and biomass. It is also considered an environmental hazard due to potential GHG emissions, and persistent

toxic substances [28, 43]. Since the major portion of the waste is organic, composting facilitates the utilization of waste carbon in the form of compost. The increasing ratio of composting from 5.4% in S2 to > 50% in S3 and S4 significantly decreases the required volume of landfills. Also, due to an increased ratio of incineration, more than half of the increased amount of waste transported into the treatment plant is wood waste from the garden in S3 and S4. Therefore, the emissions are non-fossil in origin and do not account for the GWP. Even though the waste composition affects the efficiency of incineration due to low heating values in the presence of high moisture and ash content, this still decreases the amount of organic carbon loaded to the landfill, leaving only the inorganic carbon from the incineration residues to be loaded into the landfill. The results of MFA indicate that a significant reduction of the landfill loading of solid waste can be achieved by effective source separation and considering the potential integrated approaches: such as recycling of dry recyclable wastes, composting of organic waste, and incineration of combustibles.

Table 6 Substitution options for waste treatment at different scenarios

Solid waste management system	Avoided processes		Replacement ratio (%)	Considered scenario			
				S1	S2	S3	S4
Landfilling	Gas collection	CH ₄	50	–	–	–	✓
		Recycling	Virgin material production	Plastic	90		
		Glass	95				
		Paper	90				
		Aluminum	75	✓	✓	✓	✓
Composting	Chemical fertilizer production	Fertilizer					
		7.1 kg N	0.8				
		4.1 kg P ₂ O ₅	0.5	–	–	–	✓
		5.4 kg K ₂ O	0.6				
Incineration	Electricity recovery	Electricity	8	✓	✓	✓	–
			20	–	–	–	✓

Table 7 Recycling ratios and transfer coefficients of the SWM systems

	Plastic	Glass	Paper	Aluminium/steel	Organic waste	Combustible waste	Reference	Considered scenarios
Recycling ratio 1 (%)	100	100	100	100	–	–	Personal communication with park service staff	S1, S4
Recycling ratio 2 (%)	67	43	47	60	–	–	[1]	S2, S3
Transfer coefficients								
Recycling residues (%)	25.5	0.0	11.0	16.5	–	–	[28]	S1-S4
Compost production (%)	–	–	–	–	35	–	[35]	S2-S4
Incineration residue (%)	–	–	–	–	–	17	[35]	S2-S4

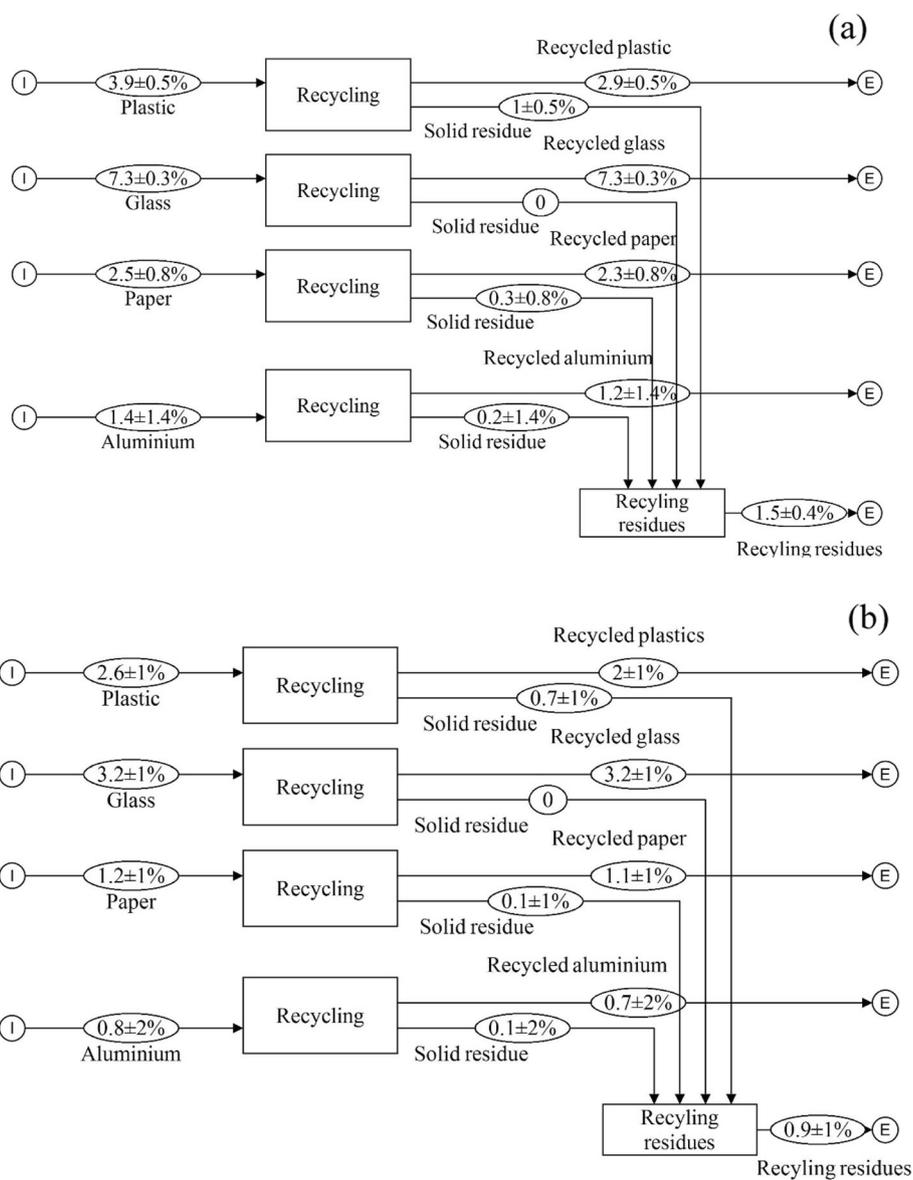


Fig. 4 Material flow analysis of the recycling system; (a), considered for S1 and S4; (b), considered for S2 and S3 (I, import flow; E, export flow; Flows (t/a))

Life cycle impact assessment

Global warming potential

Figure 5a shows the GWP in terms of total kg CO₂e emissions per scenario of waste management in CUCP. All the scenarios considered in the study were found to result in net GHG burdens (environmental loads). S1 resulted in an environmental load of 2.9E+ 05 kg CO₂e due to landfill application of waste and - 1.8E+ 04 kg CO₂e of environmental saving due to recycling, contributing a net GHG burden of 2.7E+ 05 kg CO₂e. S2, which represents the existing waste management practice in Thailand, had its dominant GHG burden contribution in the form of landfilling (2.5E+ 05 kg CO₂e), while incineration and composting contribute 290 and 100 kg CO₂e GWP, respectively. S2 and S3 considered a landfill site without gas collection and a composting facility that is not able to suppress chemical fertilizer usage. Since the energy recovery at the incineration plant (8% energy recovery efficiency) is not sufficient for offsetting the required energy for waste treatment in S2 and S3, GHG benefits of the recycling of dry recyclables (- 1.0E+ 04 kg CO₂e) alone decrease the GWP of S2 and S3, similar to S1. Increased ratio of composting and incineration to 30% in S3, decreases the amount of waste directly sent to the landfilling sites. However, S3 still represents environmental loads of 1.6E+ 05, 5.0E+ 03, and 5.3E+ 02 kg CO₂e, for landfilling, incineration, and composting of solid wastes, respectively, resulting in a net GWP of 1.5E+ 05 kg CO₂e. Avoided environmental loads due to methane and electricity recovery at the landfilling and incineration facility, and potential replacement of fertilizers due to composting decrease the environmental load of each treatment method considered in S4. However, results show that the considered ratio of gas and electricity recovery could not neutralize the potential environmental loads in the waste management system.

Contribution analysis

The contribution of process type to GWP in each scenario is presented in Fig. 5b. The contribution of waste transportation, on-site operation, and required intermediate facilities for the GWP was considered.

Results show that the transportation of waste plays a major role in GHG emissions in each waste treatment process in all scenarios. The highest GHG emission in S2, S1, and S3 is shown in waste landfilling (the GWP are 6.3E+ 03, 6.1E+ 03, and 4.2E+ 03 kg CO₂e, respectively), while in S4 transportation of combustible waste to incineration has the highest environmental burden (5.3E+ 03 kg CO₂e); this is likely due to the transportation of a large amount of combustible waste for a considerable distance for treatment compared to landfill disposal. Since it was assumed that the source segregated recyclable wastes, such as plastic, glass, paper, and

aluminium/steel were directly transported to recycling centers using a freight lorry, and due to less amount of available waste as a result of the recycling, the environmental burden of recycling is less compared to other waste treatment methods. The maximum level of waste separation at the source and point of collection minimizes the environmental burdens. Also, the selection of proper waste transportation methods considering the point of treatment and transfer stations improves the overall sustainability of the SWM.

The GWP of intermediate facilities due to required fossil fuels and combustion of fuels during operations are found to be positive, creating an environmental load for landfilling (S1–3), recycling (S1–4), composting (S2–4), and incineration (S2–4). A surplus of recovered gas in landfilling and electricity during incineration creates net GHG benefit of - 5.7E+ 02 and - 5.3E+ 03 kg CO₂e FU⁻¹, respectively due to intermediate facilities in S4. Results show the avoided GHG emissions from electricity production (with 8% efficiency) at S2 and S3 could not even offset the GHG emissions from intermediate facilities. In general, the moisture content of the waste used for incineration in Thailand is high, ranging between 40 and 60%. This requires an excessive amount of fuel to burn wet waste at the incineration plant resulting in more GHG emissions [44]. Therefore, appropriate measures should be taken to increase the energy recovering efficiency in the incineration plant and to reduce the use of other fuels by an improvement of the combustion in various ways. The GWP of intermediate facilities in the waste recycling process was found to be the highest in all the scenarios due to high energy consumption during the treatment. The GHG emissions of landfilling operations were found to result in the highest contribution to the GWP of the waste management systems (S1 > S2 > S3 > S4). Since large amounts of organic waste are dumped into a landfill in each scenario, the potential of CH₄ produced during waste degradation is significantly high, resulting in its maximum contribution to GWP. However, the GWP of the operation phase of the recycling facility was negative, creating an environmental benefit (Fig. 5b). This is likely due to the high ratio of substitution of virgin material with material recycling. Similar to recycling, composting shows a lower GHG emission potential in the operation phase than transportation and required inputs. The composting facility of S4 was found to contribute a - 3.1E+ 01 kg CO₂e GHG benefit due to considered avoidance of fertilizer application and an equivalent production of compost. GHG emissions due to the combustion of waste at the incineration facility are found to be 2.5E+ 01, 4.2E+ 02, and 5.3E+ 02 kg CO₂e for S2, S3, and S4, respectively, in line with the amount of waste considered in combustion in each scenario. However, since only the

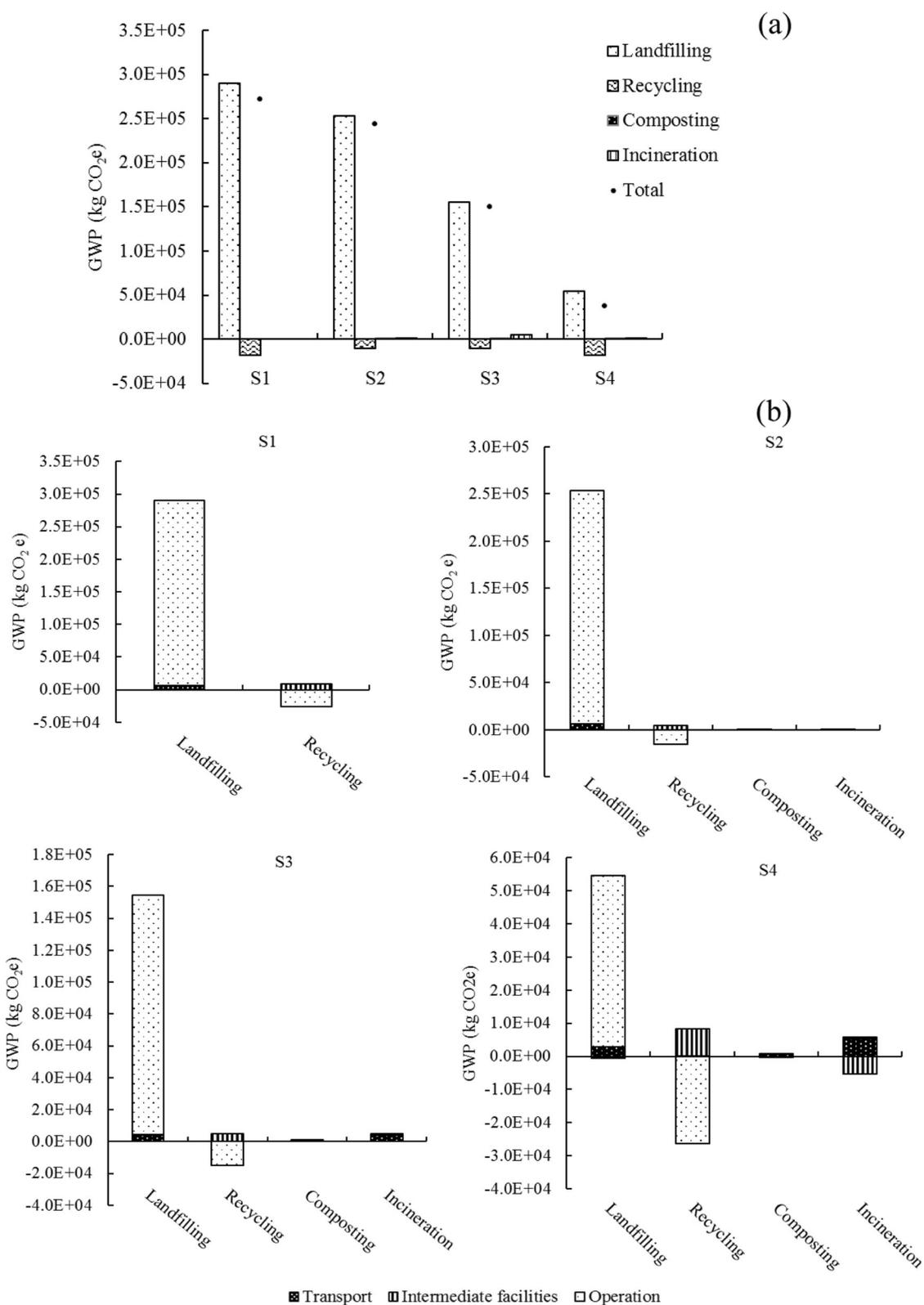


Fig. 5 Life cycle assessment (GWP, kg CO₂e FU⁻¹) of (a) different scenarios; (b) contribution of process type. Remarks: GWP, global warming potential; FU, functional unit

emissions of fossil CO₂ were considered and the highest fraction of the waste is organic, GHG emissions from waste combustion (operation) of incineration facilities are considerably low.

According to Arena and Di Gregorio [28], an integrated and sustainable waste management system should be developed in a way that minimizes the use of landfills, maximizes the recovery of materials, and maximizes the energy recovery for materials that cannot be recycled, to save both landfill volumes and fossil-fuel resources. The highest portion of generated waste in CUCP is organic with a high volume of tree leaves and barks. Therefore, composting and incineration would be potential waste treatments. Increased ratio of incineration and composting of organic waste certainly decreases the quantity of wastes loaded into landfills. This decreases the GWP of landfill disposal of wastes. Also, potential energy recovery and possible avoidance of chemical fertilizers due to incineration and compost production, respectively, decrease the environmental burdens of GWP of SWM in the park. However, high moisture and ash content, and the low heating value of garden waste limit the amount that can be sent to incineration [8]. In addition, source separation and collection assisted in the improvement of the environmental performance of waste management in the park by decreasing possible extra environmental burdens.

Overall, the results of the study show that environmental loads created by landfilling, composting, and incineration cannot be negated by recycling activities. Even though gas and energy recovery during landfilling and incineration, and possible fertilizer substitution by compost production in composting, decrease the environmental burdens in each scenario, these approaches could not offset the gross GWP of the waste management system and all of them result in a net GHG burden.

In general, landfilling of MSW contributes to the highest GWP as reported in most studies [45]. Similar to that, Liamsanguan and Gheewala [46] reported a higher net GWP of 1.6E+03 kg CO₂e from landfilling (without energy recovery) than compared to 6.5E+2 kg CO₂e from incineration (with energy recovery) of 1 t of MSW treated in a waste management system in Thailand. Menikpura et al. [38], also reported a net GHG emission of 1.2E+3 kg CO₂e from sanitary landfilling (with electricity recovery) while 5.9E+2 kg CO₂e net GHG emissions of incineration of 1 t of treated respective waste management in Thailand. These studies also suggest the possibility of the improvement of waste management systems via proper practices.

Results show that MFA facilitates a complete characterization of waste management systems providing an essential base for LCA. An integrated MFA and LCA

approach comprehensively evaluate existing and alternative waste management systems and policies. This will support the local authorities in identifying gaps and required improvements in waste management approaches. Thus, this provides a clear path towards sustainable waste management practices. However, waste management directly affects many parts of society and the economy. On the other hand, many socio-economic drivers determine the status of the efficiency of waste management systems. The quantity and the composition of MSW, as well as the efficiency of the appropriate management option, is directly governed by the socio-economic status [4, 47]. Therefore, it is required to evaluate environmental impacts considering the social acceptance and awareness along with the economic factors, to ensure the operation of a sustainable waste management system [47]. The implementation of an efficient and environmentally sound integrated waste management system ensures social, economic, and environmental sustainability.

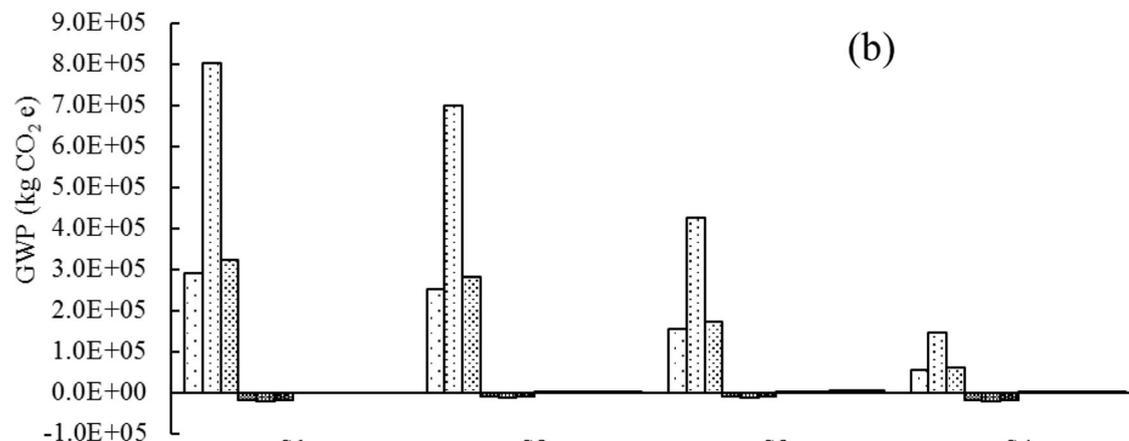
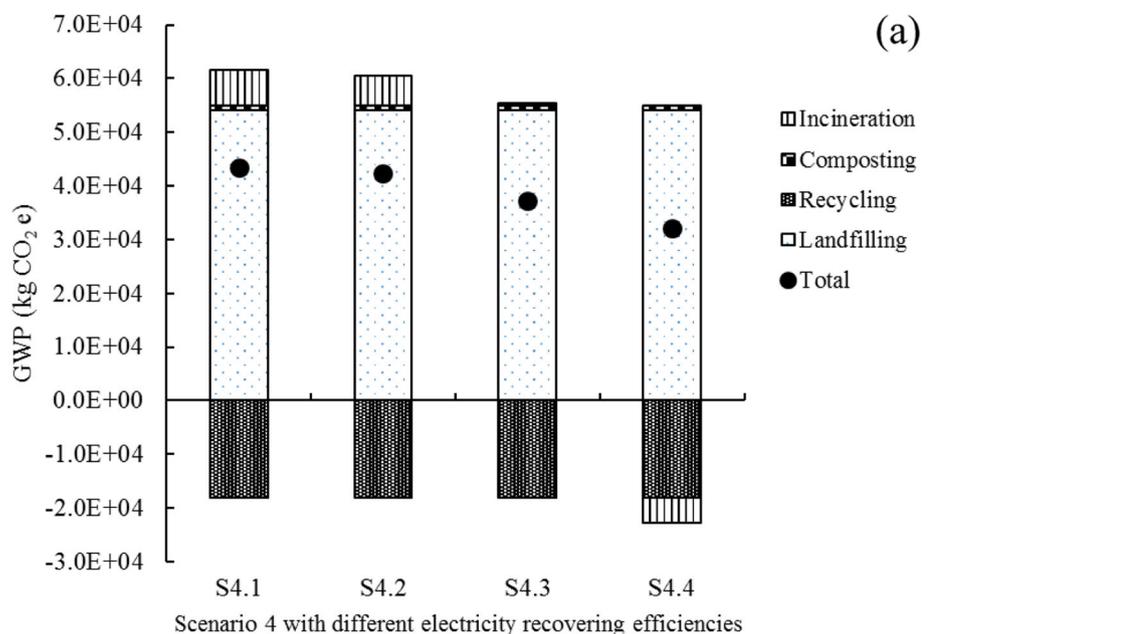
Sensitivity analysis

Two sensitivity analyses were performed to evaluate the results of the impact of GWP of the considered SWM systems. Figure 6a illustrates the sensitivity of the GWP of the considered energy recovering efficiency of the incineration plant in S4. The results show that an increase in the ratio of electricity recovery from 8 to 10, 20, and 30% decreases the GWP due to incineration from 6.7E+03 to 5.6E+03, 4.9E+02, and -4.7E+03 kg CO₂e, respectively, because the recovery of electricity replaces the same amount of required electricity production from fossil-based generation methods. Increase energy recovery efficiency from 8 to 30% was found to result in a net decrease of GHG emissions, proving that it is possible for improvements in electricity recovery in incineration plants to increase the environmental benefits of the SWM system.

The results of GWP in each scenario (IPCC 2013 GWP 100a) were compared with IPCC 2013 GWP 20a V1.03, and ReCiPe 2016 Midpoint (H) V1.01 methods. The results are shown in Fig. 6b. The mid-point assessment results of the ReCiPe method tend to be similar to the results found in IPCC 2013 GWP 100a. However, the results of GWP of IPCC 2013 GWP 20a are significantly high as the GWP of GHG at 20-yr time horizon is higher than that of 100-yr time horizon.

Conclusions

This study compares the SWM options for CUCP, Bangkok, Thailand, in 2018 using an integrated approach based on the MFA and LCA. The current municipal SWM plan in Thailand was assessed in S2, while three alternative systems with different recycling,



	S1	S2	S3	S4
Landfilling GWP 100a	2.9E+05	2.5E+05	1.5E+05	5.4E+04
Landfilling GWP 20a	8.0E+05	7.0E+05	4.3E+05	1.5E+05
Landfilling ReCiPe	3.2E+05	2.8E+05	1.7E+05	6.0E+04
Recycling GWP 100a	-1.8E+04	-1.0E+04	-1.0E+04	-1.8E+04
Recycling GWP 20a	-2.2E+04	-1.2E+04	-1.2E+04	-2.2E+04
Recycling ReCiPe	-1.8E+04	-1.0E+04	-1.0E+04	-1.8E+04
Composting GWP 100a	0.0E+00	1.0E+02	5.3E+02	8.4E+02
Composting GWP 20a	0.0E+00	1.1E+02	5.7E+02	8.9E+02
Composting ReCiPe	0.0E+00	1.1E+02	5.4E+02	8.5E+02
Incineration GWP 100a	0.0E+00	2.9E+02	5.0E+03	4.9E+02
Incineration GWP 20a	0.0E+00	3.0E+02	5.1E+03	4.0E+01
Incineration ReCiPe	0.0E+00	3.0E+02	5.0E+03	5.0E+02

Fig. 6 Sensitivity analysis of (a) S4 to electricity recovering efficiency; (b) GWP of S1–4 with different impact methods. Remarks: S4.1, S4.2, S4.3, and S4.4 refers to scenario 4 with 8, 10, 20, and 30% electricity recovering efficiency at incineration plant, respectively; Impact methods, IPCC 2013 GWP 100a V1.03, IPCC 2013 GWP 20a V1.03, and ReCiPe 2016 Midpoint (H) V1.01; GWP, global warming potential

composting, and incineration ratio were also considered. The majority of the waste generated in the Park is green wastes from garden management (81%). The results of MFA show that the highest landfill ratio is found in S2, with 101.9 t yr^{-1} solid wastes. S4 resulted in the highest recycling/composting ratio, energy recovery ratio, and the highest ratio of waste diversion from the landfill. The results of LCA show that S1 resulted in the highest GWP of $2.9\text{E}+05 \text{ kg CO}_2\text{e}$ followed by S2 ($2.5\text{E}+05 \text{ kg CO}_2\text{e}$), S3 ($1.6\text{E}+05 \text{ kg CO}_2\text{e}$), and S4 ($5.4\text{E}+04 \text{ kg CO}_2\text{e}$). Overall, waste recycling in S1–4 ($-1.8\text{E}+04$, and $-1.0\text{E}+04 \text{ kg CO}_2\text{e}$) were found to result in net environmental benefits while composting, incineration, and landfilling were found to result in net environmental burdens. S4 was found to result in the lowest GWP due to an increased ratio of recycling, composting, and incineration, and also due to gas and electricity recovery. The results of the LCA were also found to be sensitive to energy recovering efficiency during incineration. Since all the scenarios considered in the study were found to result in net GHG burdens, the requirement of upgrading the technology with a proper strategy on the waste management system in Thailand can be highlighted.

Supplementary information

Supplementary information accompanies this paper at <https://doi.org/10.1186/s42834-020-00057-5>.

Additional file 1: Figure S1. Waste management practices (a) in Thailand, 2015; (b) global level (adopted from [1, 4]). **Figure S2.** Location map of the CUCP.

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Authors' contributions

Dr. Indika Thushari is the first author responding to data analysis and manuscript writing. Mr. Juckrit Vicheanteab is the second author who collected and analyzed data under Dr. Indika's supervision. Dr. Dao Janjaroen is the corresponding author who initialized and supervised the whole work. The author(s) read and approved the final manuscript.

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Availability of data and materials

Data will not be shared due to privacy and policy of the place from which data was taken.

Competing interests

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