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Life Cycle Assessment of Integrated Municipal Organic Waste Management Systems in Thailand

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Abstract: The majority of municipal solid waste in Thailand is organic waste including food and garden waste. Improper waste management has caused negative impacts on the environment. This study aimed to find a hypothetical municipal organic waste management scenario with the lowest environmental impacts using life cycle assessment (LCA). The system boundary of organic waste management includes collection and transportation; treatment, including centralized and on-site treatment technologies; and by-product utilization. The two main waste management systems considered in this study were centralized and on-site waste management systems. The first two scenarios take into account all the amount of the municipal organic waste collected and transported and then treated by centralized waste treatment technologies (composting, anaerobic digestion, and landfill). The remaining three scenarios are integrated between 10% on-site (home composting, food waste processor, and composting bin) and 90% centralized (composting, anaerobic digestion, and incineration) waste treatment technologies; the scenario combining centralized (food waste anaerobic digestion, garden waste composting, and incineration) and on-site (home composting) systems yielded the lowest environmental impacts (except short-term climate change, freshwater, and marine eutrophication). On-site systems can help reduce collection, transportation, and treatment impacts, particularly photochemical oxidant formation, which was proportional to the amount of waste or distance reduced. Benefits from the by-product utilization can offset all impacts in terms of fossil and nuclear energy use and freshwater acidification, and result in a negative impact score or impact reduction. This research can be used as guidance for developing countries with conditions and waste composition similar to Thailand for making initial decisions on environmentally sustainable municipal organic waste management.

Keywords: environmental assessment; centralized system; on-site system; composting; anaerobic digestion; landfill; incineration; home composting; food waste processor; composting bin

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1. Introduction

Following the guidelines of Thailand's Pollution Control Department, municipal solid waste can be categorized into compostable waste, recyclable waste, hazardous waste, and general waste [1]. Compostable waste, or organic waste, includes food waste and garden waste [2]. Organic waste occupies the largest fraction of municipal solid waste (MSW) generated in developing countries, including Thailand, where it accounts for about 49% of the total amount of MSW [3]. Based on the amount of municipal solid waste generated in 2021 [4] and the waste fraction in Thailand [3], the amounts of municipal solid waste, food waste, and garden waste could be approximately estimated as 25, 9, and 2 million tons, respectively. Various pollutants released from biological reactions and leaching caused by improper management of organic waste can pose a threat to the environment [5]. The main factors influencing the food waste generation rate in developing countries are income levels, population growth rates, and urbanization rates.

Food waste is the largest fraction of municipal organic waste in Thailand. The food waste generation rate in developed countries (107 kg/capita/year) is higher than in developing countries (56 kg/capita/year). The total amount of food waste generated by developing countries such as China and India is nearly equal to that of developed countries, which are the major contributors to food waste [6]. Some developed countries have tried to control the increase in food waste by adopting a "Zero waste" policy that focuses on encouraging waste generation reduction and increasing the diversion rate of the waste. The common reasons for ineffective food waste management in developing countries are poor recovery systems, insufficient motivation in food waste recycling initiatives, inadequate policies to induce people to participate in recycling activities, lack of a legislative framework, lack of adequate and appropriate education initiatives to increase food waste sorting and collection rates, limited private sector participation, and limited funding supports [7]. In Thailand, the government has encouraged people to separate food waste at source in some cities to strengthen the implementation of the 3Rs (Reduce, Reuse, Recycle), aiming to increase the use of organic waste by 50% before 2026 [8]. In addition, the Thai government has collaborated with non-government organizations to promote the composting program by providing free organic waste bins for the public. This scheme enables the recycling of food waste and encourages people to compost across the country [9]. However, Thailand's food waste recycling system has not yet achieved significant success, mainly due to the underdeveloped food waste treatment system, lack of a market for food waste products, and insignificant economic incentives [10,11].

According to Adhikari et al. [12,13] and Thi et al. [7], the five treatment technologies implemented in developing countries for food waste management are animal feeding, composting, anaerobic digestion, incineration, and landfills. Nonetheless, animal feeding and incineration were rarely applied. The most popular waste disposal methods are illegal open dump and landfill (90%), followed by composting (1%), anaerobic digestion (0.6%), and others (8.4%). Although incineration can reduce waste volume and extend the life of landfills, it is not a popular method for food waste treatment because of the high moisture content of such waste and the need for pre-treatment processes that require high capital and operation and maintenance costs. Among the different reasons for choosing a specific technology, the utilization of by-products that promote the country's main activities is one of the most important reasons. Agriculture-based countries such as Thailand, Indonesia, etc., tend to choose composting technology to produce fertilizer while the countries with large livestock production such as China, India, etc., tend to choose animal feeding methods instead [10]. The integrated food waste management system in Taiwan is an efficient and successful system that can serve as a prototype for the treatment of food waste in developing countries.

Composting and anaerobic digestion were the municipal organic waste treatment technologies that were implemented in Thailand for treating food waste, while composting and landfill were typically used for treating garden waste [14–18]. Thailand has succeeded in integrating anaerobic digestion and composting technologies to treat food waste. The Rayong waste treatment plant in Thailand uses source-separated municipal food waste to generate organic fertilizer and biogas [7].

Garden waste is generated during the maintenance of home gardens and public parks. It is made up of both organic and inorganic components, such as grass clippings, hedge cuttings, pruning, leaves, timber, soil, and stone. Existing studies on environmental assessment of the treatment of garden waste are limited [18]. Windrow composting technology is widely used in the United States, Denmark, and Malaysia to treat garden waste [19–21] because this technology has low capital, operation, and maintenance costs. The products of composting technology can replace natural resources such as mineral fertilizer and fossil fuel. However, this kind of technology cannot control gaseous or odor emissions into the environment [22].

Garden waste is characterized as organic waste and can be considered similar to food waste according to the 3Rs principle of Thailand. The expected outcomes of following the 3Rs principle are to reduce the amount of landfill gas emissions, use organic fertilizer for cultivation instead chemical fertilizer, and generate alternative energy to reduce the use of natural sources and fossil fuels, but these principles were not brought into force [17].

Identifying the contribution of treatment processes to relevant environmental impacts will enable the Regional Waste Management Organization of Thailand to make decisions and formulate policies. Life cycle assessment (LCA) is a standardized methodology used to assess environmental impacts associated with a product, a process or a system along its life cycle [23]. This study applied the LCA framework to assess the environmental impacts of all life cycle stages of municipal organic waste management. The results would be beneficial for the decision-makers to analyze and compare the environmental performance of organic waste management technologies in a transparent manner using scientific principles. Most of the studies that evaluated environmental impacts by applying the LCA framework were usually modelled by using a single waste treatment technology to treat all kinds of municipal organic waste in each scenario and also separate centralized and decentralized systems, such as Thushari et al. [18], Kaoudom [15], Righi et al. [10], Tian et al. [24], Lu et al. [25], and Lee et al. [26]. However, some parts of garden waste cannot be treated with the same system as food waste. For example, wood (trunk or big root) cannot be decomposed by biological methods in the same period of time as other parts due to its natural structure and components.

Few studies specifically conducted research specific to environmental impact assessment or life cycle assessment of municipal organic waste management systems, including food waste and garden waste, in Thailand. Kaoudom [15] evaluated the environmental impacts and system value of food waste using various treatment technologies for a large hotel on Samui Island, Thailand. They compared five technologies: dumpsite, landfill, a centralized biogas system with an energy recovery process, a decentralized biogas system with an energy recovery process, and a decentralized composting system. The results showed that decentralized was the best option for environmental impacts and life cycle cost value. Most studies discovered that in terms of assessing the environmental impact of municipal solid waste management systems, the organic waste fraction will be centralized, separated, and treated to be treated by a single technology such as composting, anaerobic digestion, or landfill (rejected parts), so the environmental impact of technologies used for treating organic waste cannot be compared. Chandler et al. [27] evaluated the tropical island municipal solid waste strategies of the Thai islands by comparing them between mass incineration and integrated technology; anaerobic digestion for organic waste; and the rest of the waste treated by plastic waste pyrolysis, wood plastic composite production, and refuse-derived fuel (RDF) with energy capture and utilization. It was found that single waste treatment technologies such as mass incineration cause both higher environmental impacts and higher capital costs. Thushari et al. [18] evaluated material flow and environmental impact assessment using LCA of solid waste management planning in an urban green area (Bangkok, Thailand). It assessed the environmental impact of different ratios of waste recycling, composting, incineration, and landfill. The organic waste fraction includes organic (food) and garden waste. The alternative scenario in which an increasing ration of all organic waste is sent to be treated by composting results in a lower global warming potential than existing waste management strategies in which all organic waste is treated by landfill and a lower amount of organic waste is treated by composting. Chaya and

Gheewala [14] evaluated the environmental impact of two municipal solid waste to energy scenarios in Thailand by comparing environmental potential impacts of incineration and anaerobic digestion. The result showed that by-products from anaerobic digestion, both electricity and compost, were avoided in most of the total impact categories, except nutrient enrichment, where incineration performed better. Based on case studies conducted in Thailand, they concentrated on using a single technology [14,15,18,27], only using centralized treatment systems [14,18,27], concentrating only on one type of organic waste [15], and analyzing environmental impact results by using global average characterization factors in all impact categories [14,15,18,27]. As a result, these research aspects have not been addressed properly in the Thailand case study.

Existing studies on environmental impact assessment of municipal organic waste management in other countries have not compared integrated technologies and sizes of treatment systems (i.e., [28–33]). Instead, they have tended to focus on centralized and conventional treatment technologies such as composting and anaerobic digestion. Only Di Maria et al. [31] considered incineration, and the results demonstrated that incineration was more environmentally beneficial than anaerobic digestion and composting.

The assessment considering potential integrated municipal organic waste management technologies in Thailand in this work will help fulfill the research gaps. These technologies were modelled by taking into account the potential technologies that are appropriate for each type of municipal organic waste composition (food waste and garden waste), and finding the most contributing process of each waste management stage, offering some suggestions to improve the hotspots, and trying to close the previous studies gap by sensitivity analyses such as the aspect of spatial differentiation characterization factors used in the life cycle impact assessment phase and so forth, as detailed in the next sections. This study aimed (1) to assess environmental impacts of integrated organic waste management systems in Thailand, (2) to recommend the most suitable potential alternative systems, and (3) to address future solutions (i.e., new installations) that need to be implemented when the waste generation increased beyond the treatment capacity available in the existing facilities.

2. Materials and Methods

The assessment of environmental impacts was performed according to the LCA framework outlined in ISO 14040: 2006 standard [34].

2.1. Goal and Scope Definition

The goal of this study was to assess the environmental impacts of different municipal organic waste management systems in Thailand. This study focused on post-consumption food waste and garden waste from communities. This study sought to examine future solutions that should be implemented when waste generation increases beyond the treatment capacity of existing facilities requiring the construction of new facilities.

Functional unit

The functional unit applied for this assessment was 1-ton wet weight of managed municipal organic waste (food waste and garden waste).

System boundary

The system boundary of this study was "cradle to grave," which considered the entire life cycle stages of municipal organic waste management systems shown in Figure 1. By conducting research in accordance with the attributional life cycle assessment method, however, datasets were used following the allocation at the point of substitution (APOS) system model. The system boundary includes the credits and environmental burdens of by-products or residuals linked to organic waste treatment activities such as ash disposal, energy recovery, land application of compost, etc. The life cycle stages of municipal organic waste management systems consist of collection, transportation, treatment, and by-product utilization as shown in Figure 1.

Scenario Description

The two main waste management systems considered in this study were centralized and on-site waste management systems. Composting is a commonly chosen technology in the centralized system for the treatment of municipal organic waste, especially food waste and garden waste because it can decompose and stabilize the waste into compost. Anaerobic digestion is also a popular technology for treating food waste, which can be converted into renewable fuels, and nutrients for soil amendments. However, anaerobic digestion is not suitable for the treatment of garden waste (lignocellulosic biomass) due to the process inhibition in the digestion of garden waste caused by the complexity of the lignocellulosic structure (containing 10–25% of lignin) [8]. Hence, both technologies were considered to be the main elements for modelling scenarios. The energy production from garden waste has been considered as an alternative for waste reduction and utilization in several countries including USA and China [11]. According to Chapman et al. [5], all garden waste should not be burnt at incineration sites. Wet garden waste, such as leaves and grass clippings, is difficult to combust due to its high moisture content and it is not suitable for incineration. Therefore, the sorting stage is important. Some enormous roots or trunks are transferred to incineration plants because they are too massive to compost. Due to the above reason, incineration technology was included in this study as a technology option for managing garden waste. The landfill method is also used to dispose of the residues from other waste treatment processes and it can be considered as an alternative technology for disposing of large-sized garden waste (wood) in some cases where other disposal facilities have limitations.

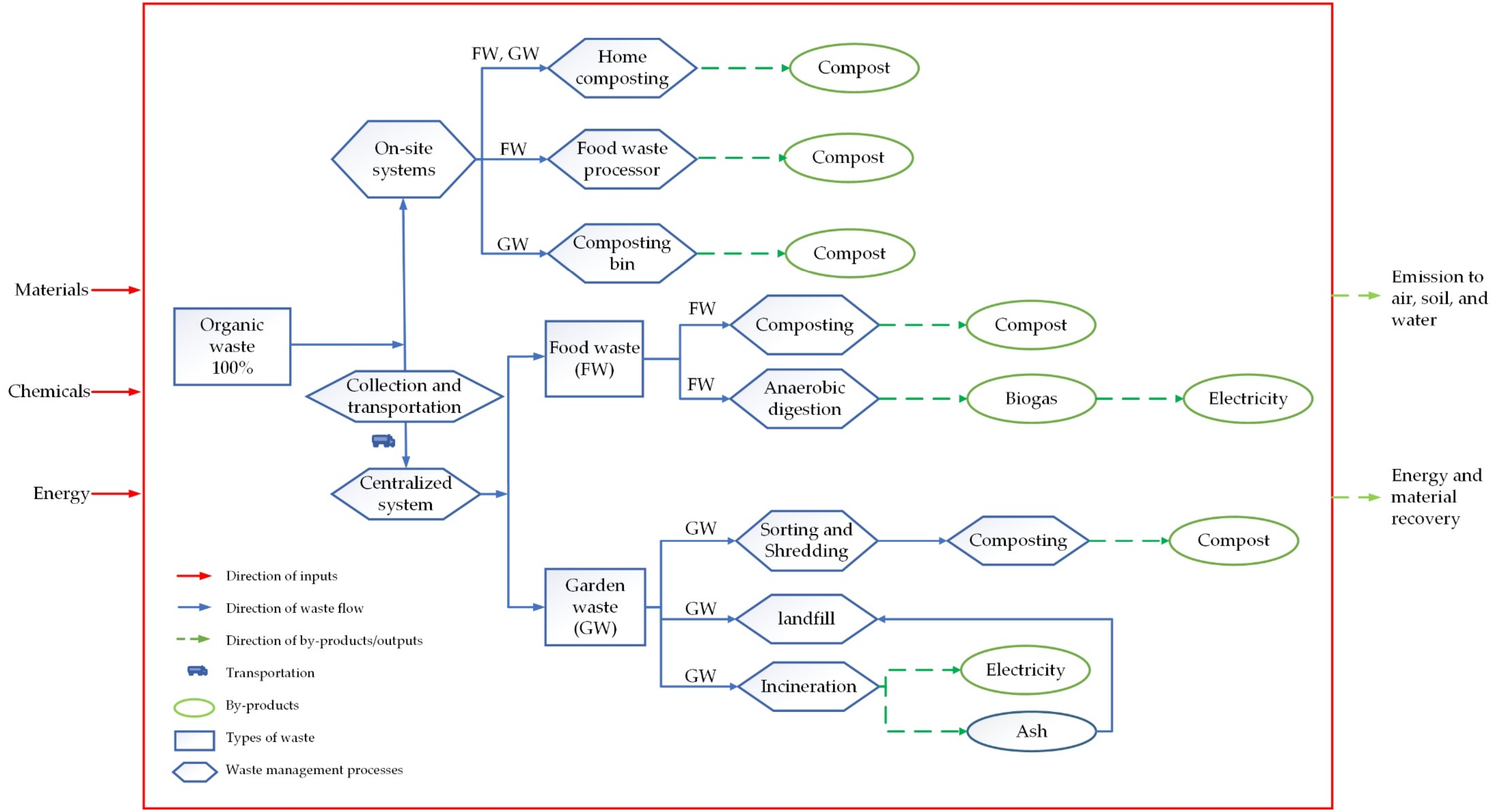


Figure 1. System boundary of the municipal organic waste management systems.

On-site waste management systems: home composting and on-site application packages (food waste processor and composting bin) can be used as an alternative to the centralized waste management system; when the treatment plant capacity is limited, waste transport to the treatment facilities is reduced, and by-products and waste utilization is extended to each household and community. Table 1 indicates the description of different technologies used to treat organic waste

Table 1. Description of organic waste management technologies.

Technologies	Waste Types	Description	By-Products (Avoided Products)
Centralized systems			
Composting	– Food waste – Garden waste	– Biological waste treatment technol-ogy is a common technology to treat organic in aerobic conditions. – No aeration and exhaust control system. – For garden waste treatment, pre-treatment systems require sorting and shredding before composting. – For garden waste, windrow composting is thought to have little leaching since the piles' low moisture content and high temperature cause initial absorption [35]. However, it is different in terms of food waste composting; as food waste has a higher moisture content, leachate would occur during composting biochemical reactions and needs to be accounted [36–38].	Compost (Chemical fertilizers)
Anaerobic digestion	– Food waste	- Biological waste treatment technol-ogy in the absence of oxygen conditions can produce bio-methane gas which is converted to electricity. – This technology is suitable for organic waste that has high moisture content.	Digestate (soil amendment) Biogas (electricity)
Incineration	– Garden waste	- Incineration is a thermal treatment-technology, which is the burning of waste at a high temperature with energy recovery system. – Due to the high water and ash content of the mixed garden waste and the low LHV, a waste separation method might be used to recover the high calorific fraction (wood and branches).	Electricity
Landfill	– Large size of garden waste – Residue from other processes (ash)	- Landfill is an engineering method for the land disposal of solid waste. - In this study, they were used to dispose of residues that remain after other processing. – Due to garden waste having a low moisture content, it is assumed that leachate is negligible.	

On-site systems

Technologies	**Waste Types**	**Description**	**By-Products (Avoided Products)**
Home composting	Mixing of food waste and garden waste	- Typically performed in small con--tainers placed in each household's backyard. - Normally, this is a mix of food waste and small-sized garden waste (50:50). - No energy is needed for transporting and operating, and there is no need for transportation for distributing compost to other locations for utilization. - There is no need for any energy supply or other input materials or substances. - Considered no pollutant-controlled process.	Compost (Chemical fertilizers)
Food waste processor	Food waste	- On-site food waste management-consists of two main stages: size reduction by crushing; and treatment (drying by heat and stabilization). It is an enclosed system. - This machine needs an electricity supply.	Compost (Chemical fertilizers)
Composting bin	Garden waste	- A composting bin is an on-site gar--den waste management technology that is aerated by using a vertical vent to increase the recirculation of air in the bin (patented aeration lung) and converts garden waste to organic fertilizer or soil amendment without the use of any electricity.	Compost (Chemical fertilizers)

As indicated by the Pollution Control Department [3], the fraction of organic waste (food waste and garden waste) in Thailand is 49.03% (food waste is 79% and garden waste is 21% on a wet weight basis) of the total municipal solid waste. The fraction of each type of waste in each scenario was modelled based on the organic waste composition indicated in Table 2. There are five scenarios for integrated municipal organic waste management systems as described by the fraction of waste at each stage in each scenario in Table 3. The existing municipal organic waste management system in Thailand is defined as the base scenario (Scenario 1 and Scenario 2) in which all food waste and garden waste are collected and transported to a centralized municipal organic waste treatment facility, which is the major system for which there is a trend to use anaerobic digestion (food waste), composting (food waste; garden waste in the form of small stuff and branches), and landfill (wood) technologies. Furthermore, alternative treatments—such as centralized incineration (wood)—and on-site technologies—which are home composting (mixed municipal organic waste), food waste processor (food waste), and composting bin (garden waste in the form of small stuff and branches)—were assessed, as were the possibilities of food waste and garden waste diversion technologies, which were modelled in Scenario 3, 4, and 5.

Table 2. Municipal organic waste composition.

Organic Waste	%	References
Food waste	79.0	[3]
Garden waste	21.0	[3]
• Small stuff	75.9	[19]
• Branches	19.6	[19]
• Wood	4.5	[19]

Table 3. Scenario description with municipal organic waste proportion.

Process	Units	Scenario 1 (S1)	Scenario 2 (S2)	Scenario 3 (S3)	Scenario 4 (S4)	Scenario 5 (S5)
Collection and Transportation	%	FW 100%	FW 100%	FW 100%	FW 93.2%	FW 93.2%
	kg	790.54	790.54	790.54	740.57	740.57
	%	GW 100%	GW 100%	GW 100%	GW 61.5%	GW 61.5%
	kg	209.46	209.46	209.46	159.46	159.46
Composting	%	FW 100%	-	-	-	-
	kg	790.54				
	%	GW 95.48%	GW 95.48%	GW 95.48%	GW 71.61%	GW 71.61%
	kg	200.00	200.00	200.00	150.00	150.00
Anaerobic digestion	%	-	FW 100%	FW 100%	FW 93.68%	FW 93.68%
	kg	-	790.54	790.54	740.57	740.57
Incineration	%	-	-	GW (Wood) 4.52%	GW (Wood) 4.52%	GW (Wood) 4.52%
	kg			9.46	9.46	9.46
Landfill	%	GW (Wood) 4.52%	GW (Wood) 4.52%	-	-	
	kg	9.46	9.46			
Home composting	%	-	-	-	FW 6.32%	-
	kg				50	
	%				GW 23.87%	
	kg				50	
Food waste processor	%	-	-	-	-	FW 6.32%
	kg					50
Composting bin	%	-	-	-	-	GW 23.87%
	kg					50

Annotation: Food waste is indicated as "FW" while garden waste is indicated as "GW".

2.2. Life Cycle Inventory (LCI)

The life cycle inventory data for Thailand were obtained from the Thai National LCI database [39]. If some data were not available in the context of Thailand, relevant data from other countries and the Ecoinvent 3.7.1 database were applied. Emissions from organic waste management systems were classified into two types: direct emissions from treatment processes and by-product utilization, and indirect emissions from materials, substances, energy inputs to the waste management system, and by-products. The direct emissions of each technology were quantified using emission factors which reflect the values related to the quantity of each pollutant emitted into the environment through the process associated with the emission of that pollutant. This study applied the emission factors obtained from IPCC [40], EMEP/EEA [41], and Nielsen et al. [42] as listed in Supplementary Materials: SM 1 emission factors at the treatment stage and SM 2 emission factors at the by-product utilization stage.

Specific data on food and garden waste management in Thailand are seldom available. Therefore, the characteristics of the waste were extracted from existing studies and guidelines to quantify the relative rate of emissions from the waste management systems using the extrapolation as shown in Table 4.

Table 4. Chemical composition and combustion data of organic waste.

Parameters	Units	Food Waste (FW)	Garden Waste (GW)	References
Moisture content	%	74	43.3	[43]
Carbon, C	% dry weight	48	47.8	[43]
Hydrogen, H	% dry weight	6.4	6	[43]
Oxygen, O	% dry weight	32.6	38	[43]
Nitrogen, N	% dry weight	2.6	3.4	[43]
Phosphorus, P	% (FW), % TS (GW)	0.11	0.11	[11,44]
Potassium, K	g/kg, % TS (GW)	10.7	1	[44,45]
Lower heating value, LHV	kWh/kg	4.56	4.35	Calculated based on Dulong's formula as cited in [43] and chemical composition from [43]
Ash	% dry weight	10	4.5	[43]

2.3. Life Cycle Impact Assessment (LCIA)

Environmental indicators or impact categories for this assessment were selected based on the substances emitted from the organic waste management system. Accordingly, the selected midpoint impact categories/indicators are:

(1) Short-term climate change: used as a proxy for the global warming potential (GWP 100), which estimates the heat absorbed by greenhouse gases.
(2) Long-term climate change: used as a proxy for the global temperature potential (GTP 100), which is related to the rise in average global surface temperature caused by greenhouse gases.
(3) Fossil and nuclear energy use: the primary energy sources. In this study, only the use of fossil fuels will be considered in accordance with the Thai context.
(4) Photochemical oxidant formation: the formation of photochemical oxidants analyzes the increase in tropospheric ozone concentration.
(5) Freshwater acidification and
(6) Terrestrial acidification: changes in pH caused by nitrogen oxides (NO_x), ammonia (NH_3), and sulfur dioxide (SO_2).
(7) Freshwater eutrophication: Phosphorus is thought to be the only limiting nutrient that causes eutrophication in freshwater. Thus, freshwater eutrophication analyzes the rise in phosphorus mass per kilogram of phosphorus discharged into freshwater.
(8) Marine eutrophication: Nitrogen is thought to be the only limiting nutrient in marine water, causing eutrophication. Thus, marine eutrophication analyzes the rise of nitrogen mass per kilogram of nitrogen discharged into marine water.

The SimaPro 2019 version 9.2.0.1 software was applied to quantify the potential environmental impacts using the IMPACT World+ characterization model [46]. The results of the life cycle impact assessment, including the percent contribution, are shown in two ways: (1) the total impact takes into account all impacts from the municipal organic waste collection and transportation and treatment stages and (2) the net impact includes the total impact and offsets from by-product utilization.

2.4. Interpretation

The impact assessment results were interpreted in the results and discussion section by identifying significant input parameters or processes of the waste management scenarios for the eight impact categories considered. Sensitivity analysis was also performed to investigate the reliability of the assessment results and their sensitivity to variable factors in LCA, as shown in detail in Table 5.

Table 5. Sensitivity analysis.

Sensitivity Analysis	Description	Related Methods/Impact Categoties/Scenarios/Factors
1	This was performed to determine the spatial differentiation between default characterization factors (global-scale) and Thai characterization factors.	• LCIA method/s: IMPACT World+ [46] • Impact categories: freshwater acidification, terrestrial acidification, freshwater eutrophication, and marine eutrophication. • Scenarios: all scenarios.
2	This was performed by determining the impact assessment method differentiation between IMPACT World+ and ReCiPe 2016.	• LCIA method/s: IMPACT World+ (main method) and ReCiPe 2016 [47] (sensitivity method). • Impact categories: terrestrial acidification, freshwater eutrophication, and marine eutrophication. • Scenarios: all scenarios.
3	This was performed by changing the organic waste fraction (food waste and garden waste) by ±10%.	• LCIA method/s: IMPACT World+. • Impact categories: all impact categories. • Scenarios: the scenario that has the lowest total impact categories. • Parameter: organic waste fraction.
4	This was performed to determine the effect of changing the collection and transportation in terms of tonne-kilometre (tkm) by ±10%.	• LCIA method/s: IMPACT World+ • Impact categories: all impact categories. • Scenarios: the scenario that has the lowest total impact categories. • Parameter: Distances travelled for waste collection and transportation, as well as the amount of waste delivered.
5	This was performed to determine the effect of changing the amount of the most contributing substance/process in each treatment technology in the scenario that has the least total impact by ±10%.	• LCIA method/s: IMPACT World+. • Impact categories: all impact categories. • Scenarios: the scenario that has the lowest total impact categories. • Parameter: the most contributing substance/process.

2.5. Assumptions and Limitations

- The data were primarily based on existing research and publications in Thailand. Nonetheless, due to the limitation of data availability, the data from other countries and international guidelines were also applied such as the fraction of garden waste [44] and the quantification of direct emissions from waste management systems.

- It was assumed that the storage of food waste and garden waste would take only a short period of time and that additional treatment processes were not required at this stage within that time period. Therefore, this stage did not include energy or input material.
- According to Chanchampee [48], the waste collection distance data were collected based on field analysis and interviews with the municipal staff. The distance was measured from the first collection point to the transfer station. The collection of MSW at the city and town levels of the municipality was around 3000 tons/day and the collection distance were 17.1 (±0.3) km. The collection of MSW at the township municipality was around 6000 tons/day and the collection distance was 17.5 km. The average collection distance of three levels of municipalities, 17.2 km, was considered as the reference value to compare the scenarios.
- According to Chanchampee [48] and a survey report on MSW management operations of all municipalities in Thailand in 2005, the waste transportation distance data were gathered based on field analysis and interviews with municipal staff. The distance was measured from the transfer station to the treatment plant. The amount of MSW transport in the city and town levels of the municipality was in the same range, which was around 600 t/day. The transportation distance was 22.2 (±0.6) km. The quantity of MSW transported in the township of the municipality was approximately 1300 t/day. The transport distance was 11.6 (±4.5) km. The average waste transport distance of three levels of municipalities, 18.7 km, was considered as the reference distance to compare the scenario.
- This study applied the "Electricity at medium voltage for Thai context dataset in the Ecoinvent database version 3.7.1 [49] for electricity use. This dataset considers the electricity available at the medium voltage level in Thailand for the year 2017. Moreover, it includes electricity inputs produced in Thailand and from imports and transformed to medium voltage, transmission network, and electricity losses during the transmission. The percentage distribution of each source of electricity generation across Thailand is: natural gas, 60.2%; lignite, 9.4%; coal, 8.4%; fuel oil, 0.1%; diesel, 0.1%; hydroelectricity, 2.3%; renewable energy, 7.4%; and imported, 12.1%.
- The assessment of this study did not include the environmental impacts of capital goods (construction of facilities and equipment). These aspects were omitted due to the perceived insignificance of environmental impacts from capital goods when compared with the other stages of municipal organic waste management and to simplify the comparison of the various scenarios proposed by Boldrin et al. [44].

3. Results and Discussion

For interpreting the results from the LCIA of the municipal organic waste management system, the municipal organic waste management system includes three main stages: collection and transportation; treatment; and by-product utilization. The three main aspects of the analyzed results are: the LCIA findings for each phase of the municipal organic waste management system; the LCIA results of modeled municipal organic waste management scenarios; and a sensitivity analysis on the important factors influencing the evaluation results.

3.1. Life Cycle Impact Assessment Results of Each Waste Management Stage

The LCIA results of each waste management stage and the most contributing sub-processes in each stage are described in this section.

3.1.1. Collection Stage

Waste collection from households was divided into these sub-processes: indirect emission from petroleum product distribution and road construction; and direct emission during waste collection. The majority of the impacts of the waste collection resulted from direct emissions that occurred during waste collection, accounting for approximately 50–90% of the total selected impacts (five of eight impact categories), while the rest of the impacts resulted from the indirect emissions caused by the process of distributing petroleum products to the final consumer, accounting for approximately 50–70% of the total selected impacts.

3.1.2. Transportation Stage

In this study, the methodology has some modelled alternative scenarios that integrate centralized and on-site municipal organic waste treatment systems. On-site treatment systems can reduce the amount of waste that must be transported and the number of rounds of transport. They are also supposed to have indirect advantages over centralized treatment systems, such as reduced fuel consumption, reduced contamination of groundwater, reduced air pollution from fossil fuel combustion, and lower road and truck maintenance impacts [50]. Waste transportation from the transfer station to the treatment plant was divided into two sub-processes: indirect emission from petroleum product distribution, truck operation and maintenance, and road construction and maintenance; and direct emission during waste transportation. The majority of the impact of waste transportation was due to the indirect emissions that occurred during the transportation of waste with the distribution of petroleum products to the final consumer and road infrastructure accounting for 60–100% of the total selected impacts (five of eight impact categories), and the remaining three impact categories resulted from the direct emissions that occurred during waste transportation, accounting for 70–85% of the total selected impacts.

3.1.3. Treatment Stage

- Food waste treatment technologies

Centralized composting was divided into these sub-processes: indirect emission of production and transportation of inputs to the composting process (water, sawdust, molasses, and truck operation); direct emission from the composting process to air and water; and by-product (compost) utilization. Centralized anaerobic digestion was divided into the following sub-processes: indirect emission of production and transportation of inputs to the composting process (water, electricity, diesel, truck operation, and lime); direct emission from the anaerobic digestion process to air and water; diesel combustion; and by-product (compost) utilization. The on-site food waste processor was divided into these sub-processes: indirect emission of production of electricity; direct emission from the composting process to air; and by-product (compost) utilization.

Anaerobic digestion has a lower environmental impact in all the considered impact categories than composting in this study, so anaerobic digestion would be the main technology for food waste centralized systems. Due to the limitation of methanogenic organisms' ability to tolerate the pH decline from acid substances produced during the hydrolysis process, chemicals are needed to control pH and maintain treatment efficiency. Sodium hydroxide (NaOH) and calcium hydroxide ($Ca (OH)_2$) are commonly used in waste treatment for pH adjustment. A preliminary assessment showed that NaOH has a higher environmental impact in all selected impact categories. Despite the fact that NaOH was found to be more effective at solubilization but has higher chemical costs than $Ca (OH)_2$, $Ca (OH)_2$ was typically chosen for food waste anaerobic digestion technology. In all the considered environmental impact categories, Scenario 1, which is modelled by using centralized composting (food waste and garden waste) and landfill (garden waste), had the highest environmental impacts because of the use of centralized food waste composting technology. Subsequently, in Scenario 2, modelled by changing food waste treatment technology to anaerobic digestion while leaving the other technologies and waste fractions of Scenario 1, the results showed that composting of food waste treatment causes higher impacts in all categories. The most contributing processes of food waste composting were the inputs of sawdust and molasses (indirect emissions), and direct emissions from the composting process.

- Garden waste treatment technologies

Centralized composting was divided into these sub-processes: indirect emission of production and transportation of inputs to the composting process (electricity and diesel); direct emission from the composting process and diesel combustion; and by-product (compost) utilization. The landfill was divided into these sub-processes: indirect emission of production, transportation, and resource extraction of inputs to the landfilling process (soil, diesel, truck operation); and direct emission from the biological reaction during the landfilling process, diesel combustion, and emission to water (leachate). Incineration was divided into three sub-processes: indirect emissions from production, transportation, and resource extraction of landfilling inputs (water, diesel, electricity, hydrochloric acid, sodium hydroxide, and lime); and direct emissions from the incineration process, diesel combustion, and emissions to soil (ash).

Due to the limitations of garden waste characteristics, composting technology is the primary method for treating small items such as leaves and branches. The most significant contribution of this method comes from direct emissions from biological degradation occurring during the composting process (six of the eight impact categories). In terms of indirect impacts, the use of diesel fuel was the significant process that caused the highest impact on the fossil and nuclear energy use and freshwater eutrophication impact categories.

The large size, hardness, and high lignin in the wood make it difficult to use biological treatment to treat within a short period of time. Therefore, landfill and incineration are the alternative technologies to treat this part of garden waste. When comparing the same amount of treated waste at the treatment stage and not including the offset impact of by-products, incineration causes a higher impact in selected impact categories (except photochemical oxidant formation). Due to the fact that landfilling of wood rarely produces by-products, when including environmental impact offset from electricity, which is the by-product of wood incineration, the overall impact of incineration is lower than landfill.

3.1.4. By-Product Utilization Stage

For composting, food waste processors, composting bins, and home composting technologies all avoid impacts resulting from the production of compost. For anaerobic digestion technology, impacts resulting from the production of electricity and compost. For incineration, it avoids those resulting from the production of electricity.

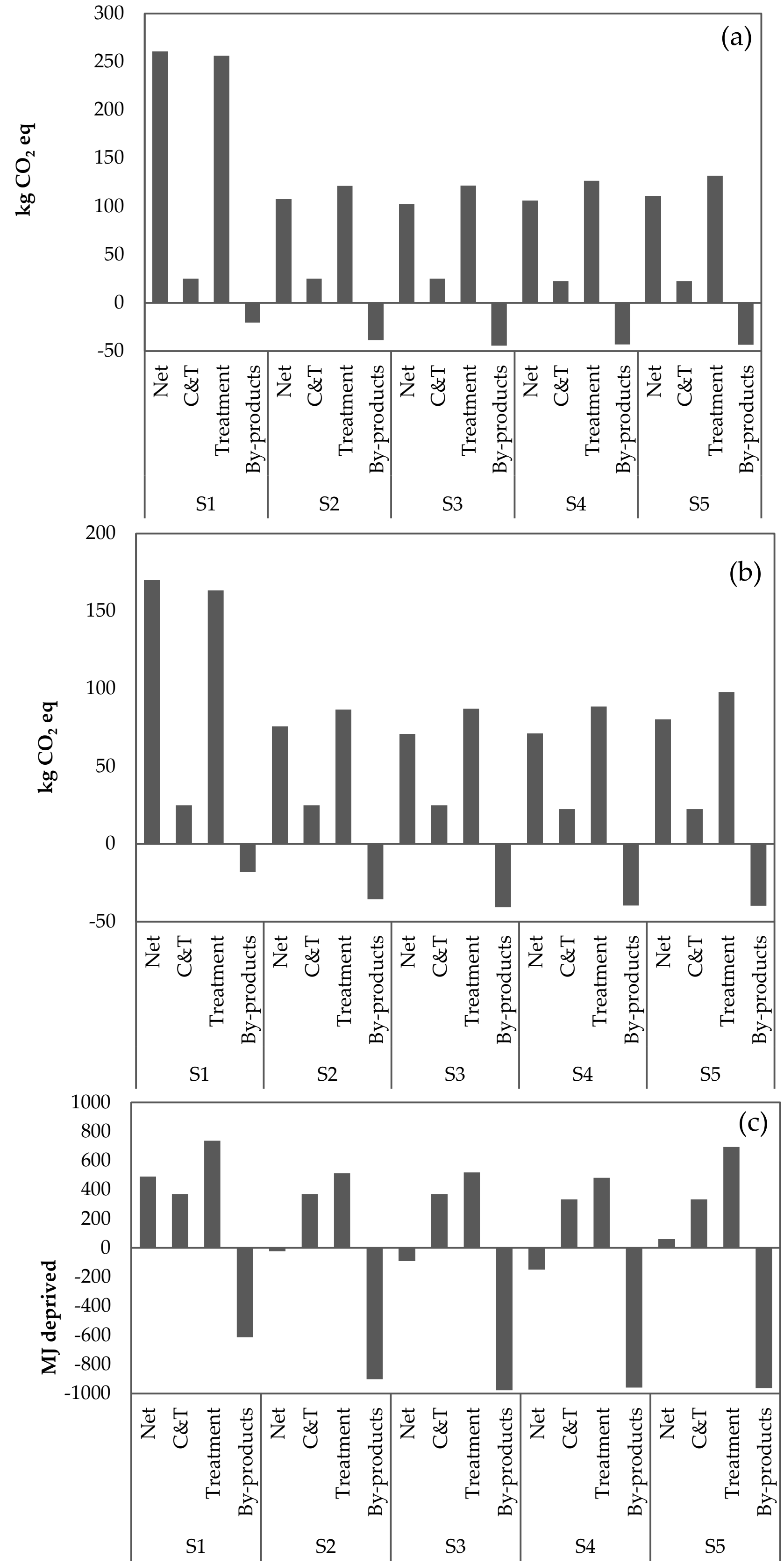
Composting and anaerobic digestion are the two main organic waste treatment technologies. Anaerobic digestion can produce more by-products that can have a higher net offset of impacts than composting. Anaerobic digestion creates compost and electricity as by-products. However, composting only produces compost from the same quantity of waste input. For by-products of anaerobic digestion, compost has a higher impact-offsetting contribution than compost, which accounts for around 61–99% of the total avoided impacts (depending on impact categories). As a result, both by-products of anaerobic digestion technology together offset most of the environmental impact categories (five of eight) by avoiding impacts significantly more than composting: climate change (short-term (145%) and long-term (155%), fossil and nuclear energy use (80%), freshwater acidification (30%), and freshwater eutrophication (12%)). For the three remaining impacts, the by-product of composting technology has higher avoided environmental impacts than anaerobic digestion: photochemical oxidant formation (23%), terrestrial acidification (82%), and marine eutrophication (142%), due to electricity from biogas combustion.

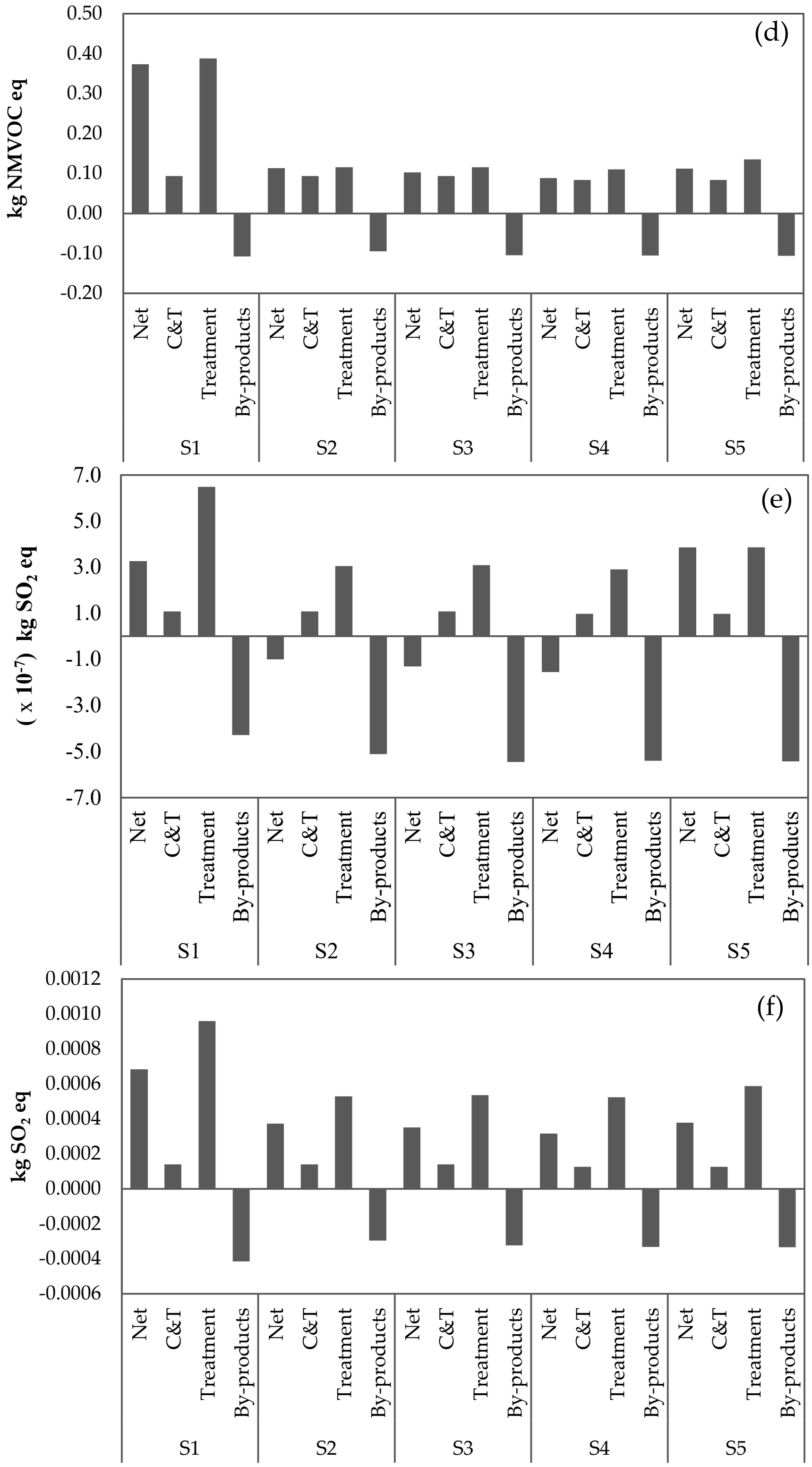
There are three centralized alternative garden waste treatments: composting, incineration, and landfill. Garden waste composting is used to treat small stuff and branches. Incineration and landfill are used to treat wood (trunk and large roots). By-products from the treatment of garden waste generated from composting and incineration technologies are compost and electricity, respectively. Most of the offsetting environmental impacts come from compost utilization, which accounts for around 60–98% of the total avoided impact from using composting and incineration together. The three on-site treatment technologies discussed in this study were home composting (combining food waste and yard waste) and two on-site treatment machines, the food waste processor and the composting bin, which convert food waste and garden waste to compost, respectively, but the operation needs to separate each type of organic waste. Compost made by home composting can be used to replace chemical fertilizer: 12.54 kg N/ton of waste, 2.03 kg P_2O_5/ton of waste, and 3.68 kg K_2O/ton of waste. While a combination of food waste processor and composting bin technologies yields compost that can be used in place of chemical fertilizers at 25.41 kg of N per ton of waste, 4.05 kg of P_2O_5/ton of waste, and 7.35 kg of K_2O/ton of waste, which produce higher compost than home composting due to them having the control system to reduce N. So, the combination of operating the two machines can offset more environmental impacts. However, the emissions from the use of compost will increase with the use of by-products. Therefore, it must be considered in this section as well, such as dinitrogen monoxide (N_2O) emission from compost utilization that causes effects on climate change in the short term and long term. Therefore, the combination of a food waste processor and a composting bin can produce a greater amount of nitrogen fertilizer but has a lower environmental impact offset than home composting after including the impact occurring from compost utilization.

Utilizing by-products will help reduce the overall environmental impacts of the organic waste management systems. By-product utilization from each waste treatment technology could contribute to the circular economy. Garden waste incineration can generate electricity and heat from waste burning. This biopower technology transforms renewable biomass fuels into electricity and heat instead of using fossil fuels. The benefits of by-product utilization are viable strategies for achieving environmental benefits through the efficient use of natural resources and reducing pollutant emissions that cause environmental impacts. Through anaerobic digestion, biogas can be converted into electricity, which is renewable energy. It is similar to electricity generated from incineration, which corresponds to the circular economy principle to circulate products and materials [51]. Digestion can be used as organic fertilizer for substrate or minimize the use of chemical fertilizer, which can result in the stabilization or mineralization of organic waste. Through composting, compost is produced as a by-product of the treatment procedure. When compost is used in agriculture instead of artificial fertilizers, organic waste with minimal economic value can provide benefits. It is utilized as a raw material to create new, more valuable materials, which follows the circular economy principle to regenerate nature [51]. These by-products can contribute to the development of an environmentally sustainable system while also demonstrating the use of the circular economy idea.

3.2. Life Cycle Impact Assessment of Food Waste and Garden Waste Management System Using Thai Spatially Differentiated Characterization Factors

The detailed interpretation of each considered impact category in this study is presented below. The result of each of all the impacts is presented in the bar graph in Figure 2.


(a)
kg CO_2 eq
300
250
200
150
100
50
0
-50
Net
C&T
Treatment
By-products
S1
S2
S3
S4
S5
(b)
kg CO_2 eq
200
150
100
50
0
-50
(c)
MJ deprived
1000
800
600
400
200
0
-200
-400
-600
-800
-1000


(d)
kg NMVOC eq
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
Net
C&T
Treatment
By-products
S1
S2
S3
S4
S5
(e)
(x 10^{-7}) kg SO_2 eq
7.0
5.0
3.0
1.0
-1.0
-3.0
-5.0
-7.0
Net
C&T
Treatment
By-products
S1
S2
S3
S4
S5
(f)
kg SO_2 eq
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
-0.0002
-0.0004
-0.0006
Net
C&T
Treatment
By-products
S1
S2
S3
S4
S5

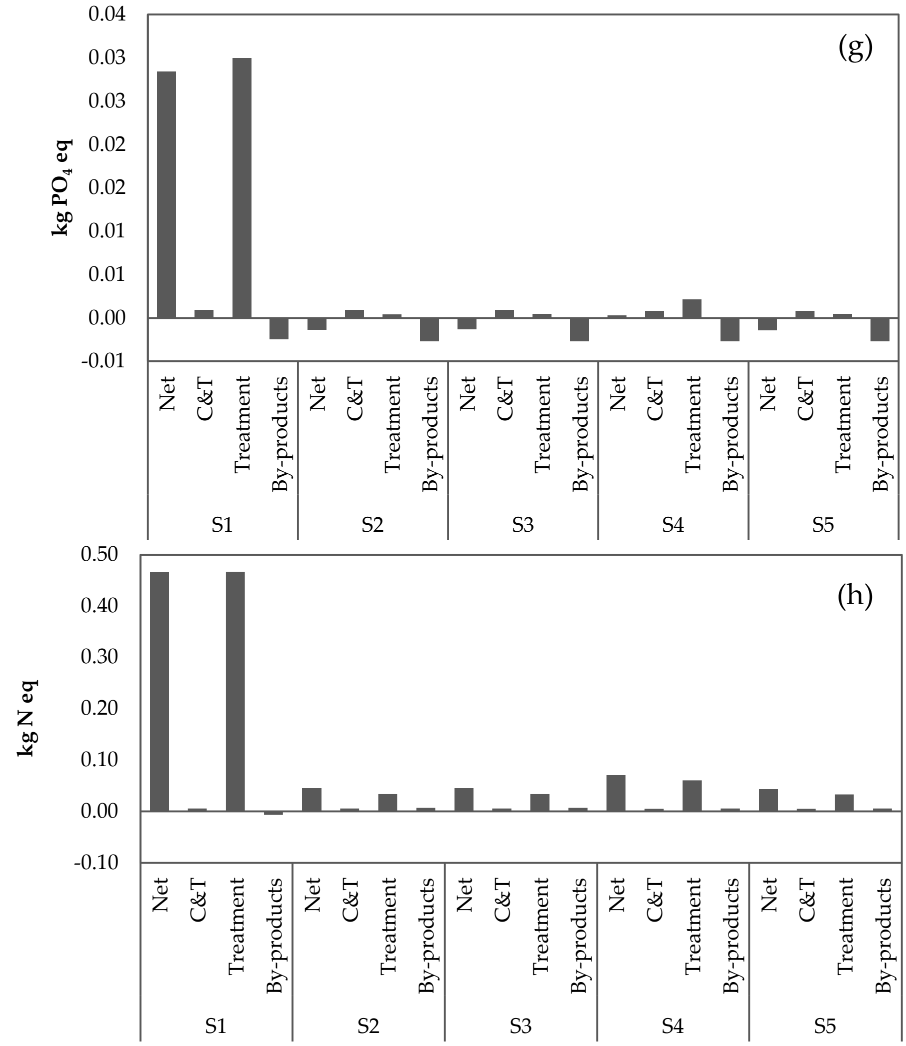


Figure 2. Life cycle impact assessment results of integrated municipal organic waste management systems. (**a**) Climate change (short term); (**b**) Climate change (long term); (**c**) Fossil and nuclear energy use; (**d**) Photochemical oxidant formation; (**e**) Freshwater acidification; (**f**) Terrestrial acidification; (**g**) Freshwater eutrophication; (**h**) Marine eutrophication.

3.2.1. Climate Change (Short Term and Long Term)

The LCIA results have shown that climate change (short term) had the same trend in all scenarios where the waste treatment stage caused the highest impacts contributing around 83 to 91% of total impacts. Scenario 1 has the highest impacts both at the treatment stage (256.23 kg CO_2 eq), total impact (281.35 kg CO_2 eq), and net impact (260.76 kg CO_2 eq), followed by the impact from the treatment stage of Scenario 5 (131.78 kg CO_2 eq), Scenario 4 (126.62 kg CO_2 eq), Scenario 3 (121.53 kg CO_2 eq), and Scenario 2 (121.20 kg CO_2 eq) as shown in Figure 2a. In addition, Figure 2a indicates that changing only the centralized food waste treatment technology from composting in Scenario 1 to anaerobic digestion in Scenario 2 enables a reduction in climate change impact by 53% as compared to the total impact. On the other hand, Scenario 2 has the lowest total climate change impact (short term) when compared with Scenario 4 and 5, which is an integrated system of centralized and on-site systems with the same amount of total amount of waste treated. There is not much difference: 2% and 5%, respectively.

The long-term climate change assessment results showed the same trend as the short-term ones, but the impact score was lower than in all stages and scenarios, at around 29 to 38 percent of treatment stage impacts, 22 to 33 percent of total impacts, and 28 to 35 percent of net impacts, as shown in Figure 2b.

The centralized food waste composting process was the hotspot process of Scenario 1 and contributed to direct emission in both short-term and long-term climate change (164.05 kg CO_2 eq and 91.13 kg CO_2 eq, respectively). However, in the short term, biogenic methane (108.00 kg CO_2 eq) was the main contributing pollutant, while, in the long term, it was dinitrogen monoxide (56.3 kg CO_2 eq). The minor contributing processes were garden waste composting (direct air emissions), followed by the collection and transportation stages.

For on-site organic waste treatment technologies, home composting could be an alternative since it is usually located in the household backyard and no requirement for electricity and fuel to manage it. Moreover, home composting does not need to maintain/ control specific operational conditions and has no pollution. Compared to the co-operation of a food waste processor and a composting bin with the same treatment capacity, home composting causes a lower impact at the treatment stage and higher avoided product environmental impact due to the food waste processor's need for electricity supply.

3.2.2. Fossil and Nuclear Energy Use

In all scenarios, waste treatment was the highest contributing stage of the organic waste management system. As shown in Figure 2c, Scenario 1 had the highest impact in treatment stage (735.04 MJ deprived), total impacts (1104.32 MJ deprived), and net impacts (489.53 MJ deprived) followed by the impact from the treatment stage of Scenario 5 (693.00 MJ deprived), Scenario 3 (517.39 MJ deprived), Scenario 2 (511.12 MJ deprived), and Scenario 4 (480.67 MJ deprived). The most contributing processes of the treatment stage in Scenario 1 were from food waste composting (709.65 MJ deprived), of which the main contributing sub-process was the input of sawdust (582.88 MJ deprived, 53% of total impacts). The collection (318.15 MJ deprived) and transportation (51.13 MJ deprived) stages had a relatively lower contribution. The results of Scenarios 4 and 5 (which used both integrated centralized and on-site waste treatment systems) show that a 10% reduction in waste collection (286.71 MJ deprived) and transportation (45.93 MJ deprived) reduced the environmental impact by approximately 10% (332.64 MJ deprived) from the used centralized waste management systems only.

3.2.3. Photochemical Oxidant Formation

In all scenarios, the waste treatment phase was the major contributor to the environmental impact of the organic waste management systems. Figure 2d depicts that Scenario 1 had the highest impact in the treatment stage (0.39 kg NMVOC eq), total impacts (0.48 kg NMVOC eq), and net impacts (0.37 kg NMVOC eq), followed by the impact from the treatment stage of Scenario 5 (0.13 kg NMVOC eq), Scenario 2 (0.12 kg NMVOC eq), Scenario 3 (0.12 kg NMVOC eq), and Scenario 4 (0.11 NMVOC eq). Composting of food waste (0.37 kg NMVOC eq), of which the main contributing sub-process was the input of sawdust (0.29 kg NMVOC eq, 60% of total impacts), was the most contributing process in Scenario 1. The second-highest contributing process was from the collection (8.54×10^{-2} kg NMVOC eq) stage followed by transportation (7.61×10^{-3} kg NMVOC eq). The results of Scenarios 4 and 5 (which used both integrated centralized and on-site waste treatment systems) showed a 10% reduction in waste collection (7.70×10^{-2} kg NMVOC eq) and transportation (6.83×10^{-3} kg NMVOC eq) from the used centralized waste management systems only. Scenario 4 had the lowest total impact, even though by-products from this scenario can offset lower than those from Scenario 1. The impacts from the collection and transportation and treatment stage in Scenario 4 were lower by 10% and 71%, respectively, compared to Scenario 1.

3.2.4. Freshwater Acidification

The treatment stage had a significantly higher environmental impact compared to the other stages in all scenarios. In particular, Scenario 1 had the highest total impact (7.55 × 10^{-7} kg SO_2 eq) and the treatment stage impact (6.48 × 10^{-7} kg SO_2 eq), which was clearly different from other scenarios (around 3.00 × 10^{-7} kg SO_2 eq). As illustrated in Figure 2c, the second-highest impact from treatment stage belonged to Scenarios 5 (3.85 × 10^{-7} kg SO_2 eq) followed by Scenario 3 (3.08 × 10^{-7} kg SO_2 eq), Scenario 2 (3.04 × 10^{-7} kg SO_2 eq), and Scenario 4 (2.90 × 10^{-7} kg SO_2 eq). The most contributing process to the total impact of Scenario 1 was in the treatment stage; the main contributing processes were food waste composting (6.18 × 10^{-7} kg SO_2 eq), of which the main contributing sub-process of food waste composting was the input of sawdust (4.10 × 10^{-7} kg SO_2 eq, 99% of total impacts). The second-highest contributing process was the collection (8.89 × 10^{-8} kg SO_2 eq) and transportation (1.85 × 10^{-8} kg SO_2 eq) stages.

Scenario 4 had the lowest total impact (3.87 × 10^{-7} kg SO_2 eq) and net impact (−1.54 × 10^{-7} kg SO_2 eq) compared to other scenarios because the utilization of by-products in various integrated waste treatment technologies (centralized and on-site systems) reduced the environmental impact. The environmental impact was lower in Scenario 1 in both the collection and transportation stages (10% lower) due to the on-site treatment system, so the amount of waste needing to be collected and transported was lower (54% lower impact). In addition, on-site treatment of waste reduced the burden on the centralized waste management system.

3.2.5. Terrestrial Acidification

The treatment stage had a significantly higher environmental impact compared to the other stages in all scenarios. In particular, Scenario 1 had the highest the treatment stage impact (9.59 × 10^{-4} kg SO_2 eq), total impact (1.10 × 10^{-3} kg SO_2 eq) and, and net impacts (6.83 × 10^{-4} kg SO_2 eq), which clearly differed from other scenarios in terms of treatment stage (around 5.00 × 10^{-4} kg SO_2 eq). Scenario 5 had the second-highest impact (5.88 × 10^{-4} kg SO_2 eq) followed by Scenario 3 (5.36 × 10^{-4} kg SO_2 eq), Scenario 2 (5.28 × 10^{-4} kg SO_2 eq), and Scenario 4 (5.23 × 10^{-4} kg SO_2 eq), as shown in Figure 2f. Composting of food waste (7.98 × 10^{-4} kg SO_2 eq) and the input of saw dust (3.46 × 10^{-4} kg SO_2 eq, 31% of total impacts) were the most contributing processes to the highest total impact in Scenario 1. The least contributing process was the direct emission (1.43 × 10^{-4} kg SO_2 eq, 13% of total impacts) from the garden waste composting process. Scenario 4 had the lowest total impact. The environmental impact was significantly lower in the treatment stage (45% lower impact). The main environmental impact being offset by by-products from garden composting (−1.14 × 10^{-4} kg SO_2 eq) caused the lowest total impact in Scenario 4.

3.2.6. Freshwater Eutrophication

According to LCIA results as shown in Figure 2g, in Scenarios 1 and 4, the treatment stage had the highest impact than other stages. Scenario 1 had an impact at the treatment stage 3.00 × 10^{-2} kg PO_4 eq (97% of total impact), which was higher than other scenarios by around one to two orders of magnitude, which resembles Scenario 4 having an impact at the treatment stage 2.18 × 10^{-3} kg PO_4 eq (73% of the total impact). In Scenarios 2, 3, and 5, the collection and transportation stages were the most contributing processes which had the highest impact compared to other stages, with contributing impacts of around 67%, 65%, and 63% to the total impact, respectively. The total impact sorted from highest to lowest value were Scenario 1 (3.09 × 10^{-2} kg PO_4 eq), Scenario 4 (3.00 × 10^{-3} kg PO_4 eq), Scenario 3 (1.39 × 10^{-3} kg PO_4 eq), Scenario 2 (1.36 × 10^{-3} kg PO_4 eq), and Scenario 5 (1.29 × 10^{-3} kg PO_4 eq). Scenario 5 had the lowest total impact. The important process that caused this scenario to have the lowest total impact was the by-product utilization of various waste treatment technologies. In this scenario, by-products of anaerobic digestion of food waste were used, with 1% of the offset impact recovered as electricity and the remaining 99% used as compost.

3.2.7. Marine Eutrophication

Of all the LCIA results, the treatment stage had the highest impact, especially in Scenario 1 (0.47 kg N eq), which contributed 99% to the total impact. The main contributing process was the direct emission (to water) of food waste composting (0.42 kg N eq). For this impact, there was a different trend in the part of the scenario that had the lowest total impact. Scenario 5 had the lowest total impact for this impact category. When comparing Scenario 5 with Scenario 4, which is usually the lowest-impact scenario, home composting which is the on-site technology that treats food waste and garden waste (Scenario 4) had the highest marine eutrophication potential than the combination of a food waste processor and a composting bin at the same weight of waste treated. In addition, it gave a lower offset impact from by-products for this impact category.

Based on the results of the comparison of different food waste treatment technologies, which corresponds to Mondello et al. [52], the anaerobic digestion of food waste has lower energy use, acidification, eutrophication, and global warming than food waste composting systems, both with and without including avoided products. Furthermore, it shows the same trend as in the study by Kaoudom [15] because of the lower direct emissions from the treatment stage and the higher environmental benefit of two by-product utilizations, electricity from biogas combustion and compost from digestate, and in accordance with the result that a centralized organic waste management system has a higher impact than the onsite system on the part of waste transportation. For the on-site organic waste treatment technologies, the results of this study are in accordance with the study of Lundie et al. [53] that found home composting is preferable to food waste processors since the food waste processor requires energy supplies.

3.3. Sensitivity Analysis

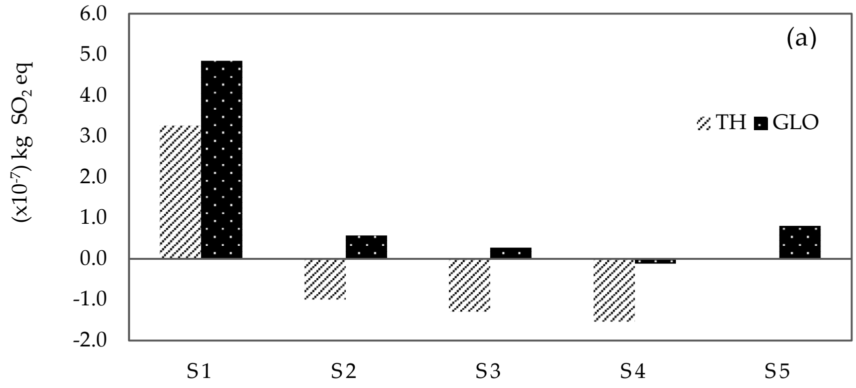
3.3.1. Spatial Differentiation

Existing LCA studies in Thailand have applied life cycle impact assessment methods which have characterization factors at the global level and do not reflect the local environmental conditions in Thailand. This could significantly affect the outcomes of the research. Therefore, applying life cycle impact assessment methods for Thailand to assess the impacts at the local level will make the assessment results more accurate and reliable. To identify the effects on implications from spatially differentiated impact assessment, Thailand-specific characterization factors for local emissions and global average characterization factors (default value) for supply chain emissions (indirect) were applied. Thailand-specific characterization factors for the emissions directly emitted from organic waste management technologies were obtained from the IMPACT World+ (version 1.29) method and adapted in the SimaPro by changing several characterization factors to be specific to Thailand.

The characterization factors vary based on spatial differentiation due to fate and transport factors vary based on location and exposure factors used to calculate the characterization factors in each area. Only the impacts of acidification and eutrophication, which were considered in this study, have Thailand-specific characterization factors in IMPACT World+, the most recent updated life cycle impact assessment method, so these two impacts will be the main impacts to be representative for this sensitivity analysis. The comparison of LCIA results of acidification and eutrophication impacts are shown as follows.

Differentiated CFs for Local Emissions (TH) and Global Average CFs (GLO) of Freshwater Acidification and Terrestrial Acidification

The global average CFs of freshwater and terrestrial acidification for pollutants such as ammonia (GLO CFs: 1.96 × 10^{-6}, 3.70 × 10^{-3} kg SO_2 eq for freshwater and terrestrial acidification, respectively) are one order of magnitude higher than Thai CF values (TH CFs: 1.43 × 10^{-7}, and 1.08 × 10^{-3} kg SO_2 eq for freshwater and terrestrial acidification, respectively). At each coarser level of spatial resolution, world characterization factors are analyzed, accounting for the additional uncertainty associated with less precise information about where the emission occurs, which may cause the global average characterization factors to have a higher value than country-specific characterization factors. Ammonia is a basic pollutant that generally arises from biological waste treatment processes and is classified as a major freshwater acidification pollutant. It was included in all the LCI data in biological waste treatment methods, which were modelled to handle both food waste and garden waste. Consequently, as illustrated in Figure 3, the LCIA results for all scenarios in this impact category, quantified using global average CFs, were higher than those using Thai CFs. However, the high and low trends in the total environmental impact rating of each scenario remained the same. Scenario 1 was still the situation with the highest total impact, and Scenario 4 was still the situation with the least total impact.



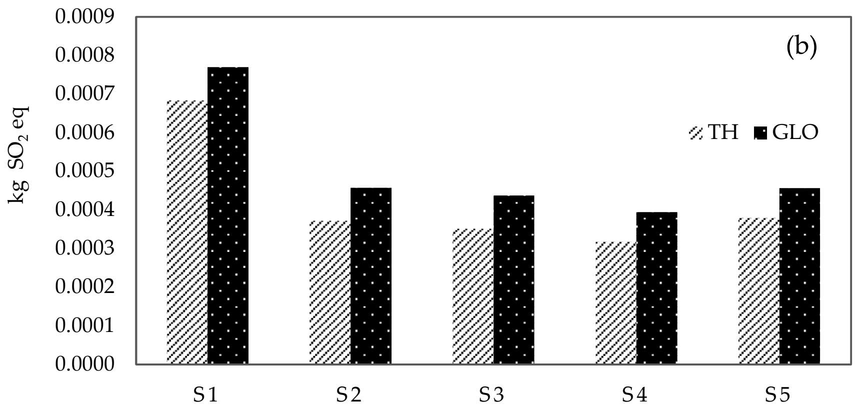


Figure 3. Life cycle impact assessment results of different characterization factors between local emissions (TH CFs) and the global average (GLO CFs) of freshwater acidification and terrestrial acidification result. (**a**) Freshwater acidification; (**b**) Terrestrial acidification.

Differentiated CFs for Local Emissions (TH) and Global Average CFs (GLO) of Freshwater Eutrophication and Marine Eutrophication

Even though the CFs of freshwater eutrophication at the global level are higher than the local level (Thailand), such as phosphate (GLO CFs: 0.32 and TH CFs: 0.03 kg PO_4 eq/kg), the LCIA results analyzed by both CFs levels are the same, as shown in Figure 3a. Because all the categorized substances under this impact category are from indirect emissions, the calculated impact scores rely on GLO CFs. The trend in the LCIA results can confirm that the assessment results are accurate and acceptable.

For marine eutrophication impact, only two substances have Thai-specific CFs. They are important substances such as ammonia, which is one of the normal pollutant emissions that occurs during organic waste management systems. Global CFs in this impact category are much lower than Thai CFs (GLO CFs: 0.06 kg N eq/kg vs. TH CFs: 0.1 kg N eq/kg). Thus, the LCIA results analyzed by using Thai CFs are higher than those using GLO CFs, as shown in Figure 4b, and the trend in the results is the same, so we can confirm that the analyzed LCIA results were reliable.

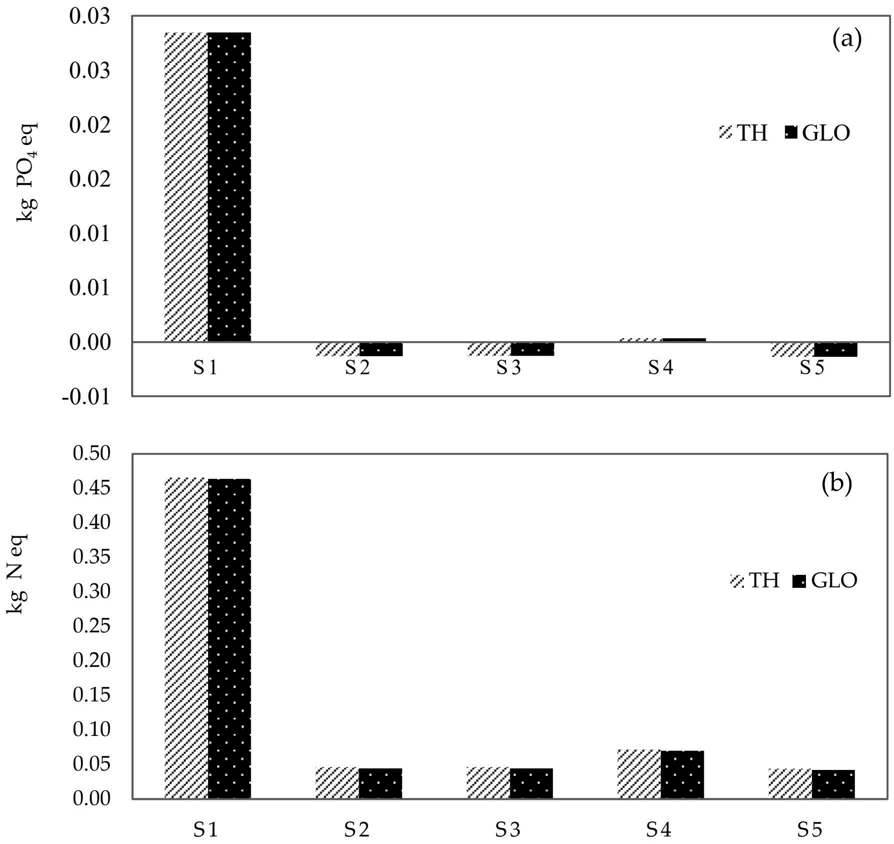


Figure 4. Life cycle impact assessment results of different characterization factors between local emissions (TH CFs) and the global average (GLO CFs) of freshwater eutrophication and marine eutrophication results. (**a**) Freshwater eutrophication; (**b**) Marine eutrophication.

According to the assessment results, all scenarios of the food waste management technologies both analyzed by using GLO and Thai CFs have the same trend. Thus, the results from the comparison can imply that they were consistent or aligned.

3.3.2. Method Variability

Different LCIA methods apply different modelling pathways which can differ in the covered impact categories, geographic scope, and modelled cause–effect chain. The most appropriate characterization model to assess eutrophication and acidification in the Thai context was selected by comparing two existing LCIA methods, ReCiPe 2016 and IMPACT World+, which have updated spatially differentiated characterization factors for Thailand. The results of the comparison are shown in Figure 5. Terrestrial acidification and marine eutrophication impact assessment results from both methods have the same trend; Scenario 1 has the highest total impact, and the hotspot process comes from the treatment stage, food waste composting (indirect emission of sawdust input material to the composting system), and Scenario 4 has the lowest total impacts. For freshwater eutrophication impact, the trends in the highest impact scenario are different for the two methods of analysis, but the trends in the scenarios with the lowest impact are quite similar. Scenario 5 has the lowest total impacts for the IMPACT World+ method and Scenario 4 for the ReCiPe 2016 method. However, there are also important points that give similar results. Scenarios 4 and 5 are the integrated centralized and on-site waste management systems. The results assessed from the two different LCIA methods can imply that integrated centralized and on-site waste management systems have lower impacts than using centralized systems only.

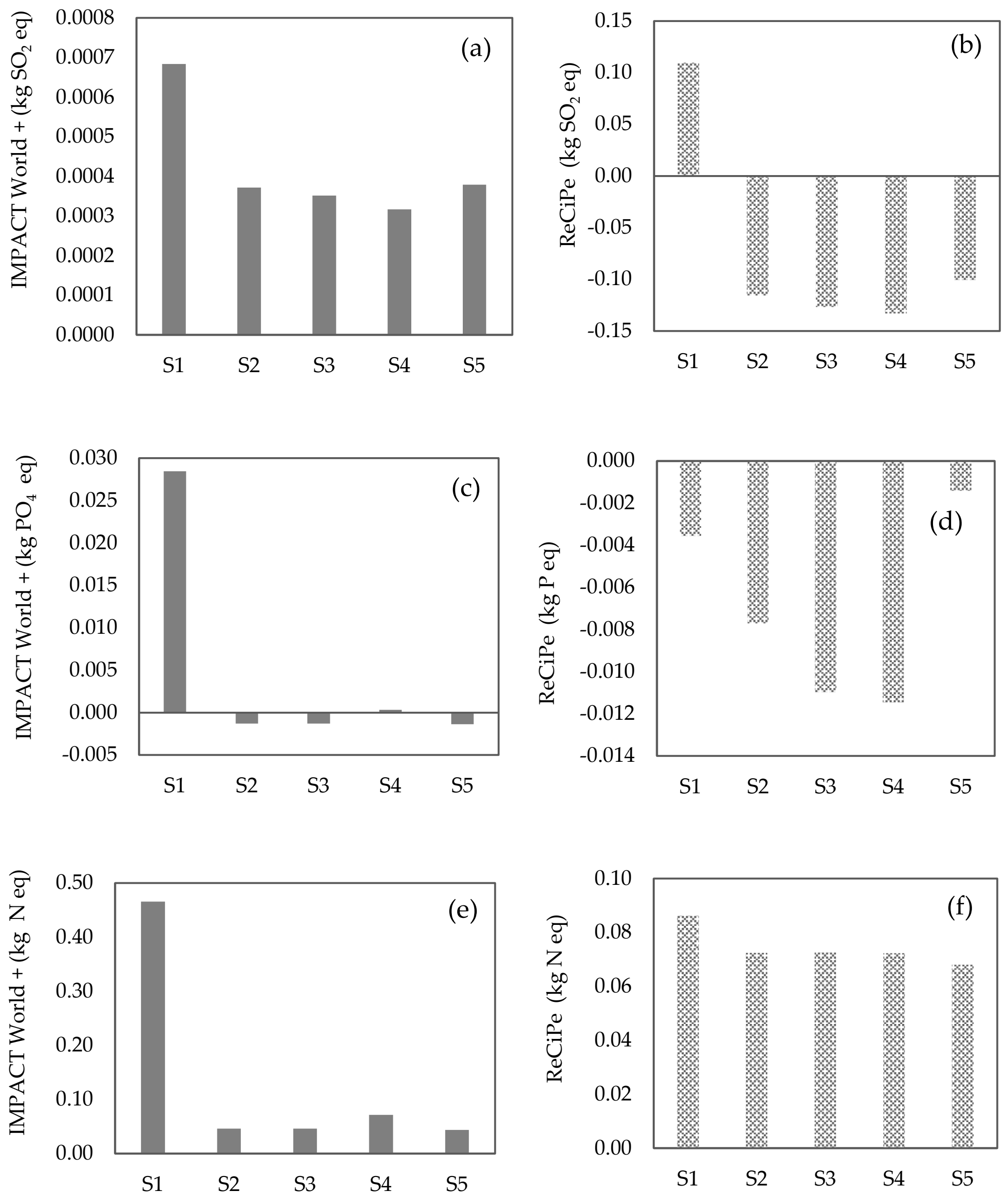


Figure 5. Comparison of life cycle impact assessment results at midpoint level between IMPACT World+ method (**a**,**c**,**e**) and ReCiPe method (**b**,**d**,**f**). (**a**,**b**) Terrestrial acidification; (**c**,**d**) Freshwater eutrophication; (**e**,**f**) Marine eutrophication.

The ReCiPe 2016 method covers fewer emission compartments and substances than the IMPACT World+ method. IMPACT World+ has midpoint characterization factors for both freshwater and terrestrial acidification in the Thailand context, but ReCiPe 2016 has only terrestrial acidification. So, the LCIA results comparison was considered for only three impacts: terrestrial acidification, freshwater eutrophication, and marine eutrophication in each scenario, for which the impacts have Thai characterization factors. The characterization factors for terrestrial acidification from ReCiPe 2016 are higher than IMPACT World+ by around one to three orders of magnitude. The characterization factors for freshwater eutrophication and marine eutrophication from IMPACT World+ are slightly higher than the ReCiPe 2016 method but are in the same order of magnitude (Supplementary Materials, SM 13). Therefore, the trend in the results of terrestrial acidification analyzed by the IMPACT World+ method is lower than that analyzed by the ReCiPe 2016 method in scenario 1. For scenarios 2, 3, and 4, the total terrestrial acidification impacts are negative due to the higher offsetting impacts analyzed by the ReCiPe 2016 method (see Figure 5a). The analyzed results by using IMPACT World+ are higher than those analyzed by the ReCiPe 2016 method in freshwater eutrophication and marine eutrophication as shown in Figure 5b,c. Based on preliminary assessment results and condition comparison as mentioned above, IMPACT World+ is more suitable for modelling spatially differentiated characterization factors if the data are available to assess municipal organic waste management in Thailand.

3.3.3. Waste Fraction Differentiation

Waste fraction differentiation sensitivity scenarios are modelled by changing food waste and garden waste by 10%. There were three modeled sensitivity scenarios, which were considered based on the waste fraction of Scenario 4, modified Scenario 4.1 (+10% FW or −10% GW), and modified Scenario 4.2 (−10% FW or +10% GW). In order to maintain the treatment conditions of the on-site treatment systems, which account for 10% of total municipal organic waste, and with the conditions of mixing the food waste and garden waste at the same ratio, the amount of waste input and environmental impacts of all sensitivity scenarios (Scenario 4.1 and 4.2) were changed only on the part of centralized waste treatment systems (anaerobic digestion, composting, and incineration). The results of changing 10% of the total amount of food waste input caused a change in the amount of food waste treated by anaerobic digestion by 13.5%. The increased amount of food waste reduced four impacts from the treatment stage by 5 to 8 percent, which were climate change in the short and long term, terrestrial acidification, and marine eutrophication, while the remaining impacts of the impacts were increased by around 1 to 10 percent. The impacts avoided from the by-product utilization stage were reduced in six impact categories: short- and long-term climate change, fossil and nuclear energy use, photochemical oxidant formation, and freshwater and terrestrial acidification, while the rest had increased impacts. The reduction in the avoided impacts from the by-product utilization stage caused a net impact reduction for five impacts, which were climate change in the short and long term, fossil and nuclear energy use, and freshwater eutrophication because the avoided impacts from by-product utilization caused a higher impact score than increasing impacts from the treatment stage. When the amount of food waste increased by 10%, the assessment results for treatment, by-product utilization, and net impacts showed the opposite trend.

The results of changing 10% of the total amount of garden waste input to municipal organic waste management caused a change in the amount of garden waste treated by composting by around 64%, a change in total impacts by around 64%, and also avoided impacts from by-product utilization by around 64%. The result of changing 10% of the total amount of garden waste caused a change in the amount of garden waste (wood parts) treated by 48%. The decrease in the amount of garden waste for incineration caused a change in total impacts and avoided impacts from by-product utilization by 45% and 46%, respectively, while the increase in the amount of garden waste for incineration caused a change in total impacts and avoided impacts from by-product utilization by 56%. The main reason for the higher change in impacts with increasing amounts compared to decreasing amounts is the indirect impacts (freshwater acidification, terrestrial acidification, freshwater eutrophication, and marine eutrophication) of ash being disposed of in landfills. A minor reason is the increased impact of indirect emissions resulting from higher inputs of material and energy to the incineration system, and the avoided impacts from increasing by-products were insufficient to offset the increasing impacts.

3.3.4. Collection and Transportation Distances

The base value for the sensitivity analysis was the result of collection and transportation in Scenario 4, which carries 0.9 tons of waste, 17.2 km of collection distance, and 16.8 km of transport distance. Based on the parameters used to calculate the impacts, the analysis was divided into two aspects: a 10% increase or decrease in both collection and transportation distance, and the amount of waste carried. The impact of collection and transportation of waste is calculated by multiplying two parameters: the amount of waste in units of tons and the distance traveled in kilometers. So, increasing or decreasing one of the parameters by 10% will give the same value of tkm unit for calculating the environmental impact and, the environmental impact assessment results will be the same when changing 10% of the amount of waste or distance.

The results from the collection stage are: collection with 15.5 tkm is the base scenario; the sensitivity scenario is 13.9 tkm, which is lower by 10% from the base value; and 17 tkm, which is higher from the base value. The results showed that when a 10% change both decreased and increased in tkm value, the impact score of all impact categories changes around 10% from the base scenario. The five impacts—fossil and nuclear energy consumption, freshwater acidification, terrestrial acidification, freshwater eutrophication, and marine eutrophication—were all most significantly (100%) impacted by the indirect emissions, which were caused by fuel acquisition, garbage trucks, and roads. While the other three impacts were the most significant, they were caused by direct emissions from stop-and-go operations, tire abrasion, brake lining, road surface and road dust re-emission, climate change in the short term (85%), climate change in the long term (86%), and photochemical oxidant formation (89%). The sensitivity analysis results for the transportation stage show the same trend as the results of the collection stage. Practically, if the positions cannot change or new treatment plants are built in the responsible area, based on the obtained results of this study, reducing the amount of waste that needs to be collected and transported by using the on-site systems would be a possible option to reduce the impacts.

3.3.5. Varying the Percentage Contribution of the Most Environmentally Damaging Substance or Process in Each Treatment Technology

Scenario 4 had the lowest impact in most of the impact categories studied. Therefore, its treatment technologies and conditions would be representative for this sensitivity analysis to determine the influence of the most contributing substance or process. By identifying and modifying the hotspot processes of each waste treatment technology in the representative scenario (Scenario 4), this sensitivity analysis aimed to improve Scenario 4, which had the least impacts of the considered impacts in this study. The sensitivity analysis was carried out by increasing and decreasing 10% of the most important input substance or process and observed how the impact score would change as a result of changing the values.

Scenario 4 consists of garden waste composting, food waste anaerobic digestion, incineration of the wood fraction of garden waste, and home composting for the mixing of organic waste (on-site technology). For garden waste composting and mixed organic waste home-composting technologies, the composting process was the most important contributing process. Depending on the impact categories, reducing gas emissions from garden waste composting by 10% can reduce the total impacts of garden waste composting (four of eight impacts) by 8–930% and home composting of mixed organic waste (three of eight impacts) by 2–13%. The impacts that did not change from reducing gas emissions from composting processes were fossil and nuclear energy use and freshwater eutrophication. The source of these impacts was mostly caused by the acquisition of diesel fuel for composting operations. By reversing piles and maintaining optimum conditions throughout the composting process, it is possible to reduce the emissions of pollutants generated during the composting process. There is also research by Sanchez-Monedero et al. [54] that uses biochar as an additive in the organic waste composting process at 10–30% rates and succeeds in mitigating NH_3, N_2O, and CH_4 emissions.

The main contributing process of food waste anaerobic digestion is electricity consumption, which accounts for around 4–63% of the total impacts (depending on impact categories) of this treatment technology. Changing electricity consumption by 10% caused a change impact score for four impacts by around 5–10% of the total impact of this technology depending on impact categories. The impact that was most affected was the photochemical oxidant formation impact (10%), which was directly related to the acquisition of electricity. The electricity generated from anaerobic digestion accounted for around 79% of the total amount of electricity consumption. At least 21% more energy recovery is needed to operate the treatment system without an external electricity supply. Xu et al. [55] have studied how to increase the efficiency of energy production from organic waste anaerobic digestion systems by the application of phase-separated anaerobic digestion, which is conducted by hydrogen and methane in separated reactors that can increase energy recovery. It may be one of the alternatives to increasing the efficiency of electricity generation from the treatment system.

The main contributing process of garden waste (wood part) incineration is electricity consumption, which accounts for around 3–92% of the total impacts (depending on impact categories) of this treatment technology. Changing electricity consumption by 10% caused a change in impact score of around 2–9% of the total impacts of this technology depending on impact categories. The impact that was most affected was the fossil and nuclear energy use impact (9%), which is directly related to the acquisition of electricity. Due to the electricity consumption of waste incineration systems, only around 10% of the electricity generated from waste is converted to energy from the burning of waste, which is enough to offset the impact of electricity consumption. Reducing humidity can increase the heating value of the waste and can result in a reduction in the amount of electricity and diesel fuel needed to maintain the temperature for burning the waste. According to Di Maria et al. [31], the only electrical efficiency for large-scale waste-to-energy systems is <24–25% and <20% for smaller systems. If we change the waste-to-energy system to a combined heat and power plant, it can increase energy efficiency by more than 70%. This can be performed by optional improvement to the system efficiency to be more environmentally friendly.

For the modelled scenarios varying the most important input substance or process of Scenario 4, if all hotspot processes can be reduced by 10%, the impact scores of six out of eight impact categories can be reduced by 1–8%. The impact reduction was mainly from the decreases in direct emission (from the garden waste composting process and home composting of mixed organic waste) and electricity inputs to the anaerobic digestion process.

4. Policy Recommendations on Future Integrated Municipal Organic Waste Management Systems in Thailand

Based on the results of this study, a few policy recommendations can be provided:

For collection and transportation, reducing the amount of municipal organic waste delivered to be treated by centralized systems by dividing some parts of waste to be disposed of by on-site systems, reducing the distance by changing the location that provides waste treatment services, or constructing new waste treatment facilities that use shorter transportation distances can reduce environmental impacts. Another option is to set up a garbage collection point in a small community instead of collecting from each house. The impacts can be reduced by at least the same percentage of the amount or distance reduction. Municipal organic waste should be separated at the source and collected separately because of the increased amount of organic waste recovery. As supporting data from the study by Chanchampee [48], composting and anaerobic digestion in Thailand rely on processing mixed MSW, resulting in low-quality compost and biogas products, and difficulties in unit operation.

It is recommended to reduce the amount of the highest contributing substances/energy input/direct emissions from the treatment processes of each waste treatment technology. Electricity has the highest contribution to the environmental impacts of anaerobic digestion and incineration technologies. Direct emissions from composting, home composting, and composting bins require additional control of the pollutants or maintaining an aerobic condition to reduce the methane and dinitrogen monoxide emissions, which have a high global warming potential. In the case of an urban area with limited space and time to operate an on-site system, the home composting system, in Scenario 4, the food waste processor, and composting in Scenario 5, might be preferable.

It is encouraged to use the by-products of the waste management system to minimize environmental impact and to avoid additional impact through the generation of by-products. For instance, if compost is not utilized as an organic fertilizer for agriculture, the nitrogen and phosphorus in compost can induce acidification and eutrophication impacts on the environment and other environmental burdens that cannot be subtracted from the by-products that produce the management systems.

Although life cycle inventory data on the waste management systems were primarily from Thailand, the data sources and quality are varied. Moreover, some existing data collected by relevant authorities/institutions were not accessible. Government agencies and the private sector engaging with the waste management in the country are therefore encouraged to systematically collect waste management data. Such data should be publicly disseminated or accessible. This will be useful not only for research work but also for national policies and planning.

To obtain reliable impact scores that reflect Thai environmental conditions, spatially differentiated characterization factors are recommended to be applied in the impact assessment. ReCiPe 2016 and IMPACT World+ are two recently updated approaches with spatially differentiated CFs. However, in the Thai context, ReCiPe 2016 excludes some of the released compounds, compartments, and sub-compartments, as well as freshwater acidification at the midpoint level. As a result, the IMPACT World+ method is the more appropriate LCIA method at the midpoint level for analyzing the environmental impacts of integrated municipal organic waste management systems in Thailand in the current circumstances.

The quantity, waste separation, and collection model of municipal organic waste, as well as the selection of treatment technologies and by-product utilization options, are, however, directly governed by each municipality's socioeconomic status and support from central government agencies that play a role in both policy and budget. To ensure the operation of a sustainable waste management system, it is necessary to examine environmental implications while also taking social acceptance and awareness into account. The establishment of an integrated waste management system that is both efficient and environmentally sound would provide supporting data for decision-makers or stakeholders to achieve social, economic, and environmental sustainability.

5. Conclusions

This study compared the environmental impacts of integrated municipal organic waste management options for Thailand. The integrated system yielding the lowest environmental impacts (five out of eight impact categories) was the integrated centralized and on-site treatment technologies, including centralized anaerobic digestion (food waste), centralized composting (garden waste), centralized incineration (wood part of garden waste), and on-site home composting (food waste and garden waste). This is because the integration between centralized and on-site systems can reduce the amount of waste that has to be collected and transported, offsetting various by-product utilization methods. It also reduces the energy needed to operate the centralized system due to home composting (on-site) and the need for an external energy supply. The integrated system with the highest environmental impacts involves the use of integrated centralized waste treatment technologies: centralized composting (food waste and garden waste) and the landfill (wood waste). This is due to the high direct emissions from composting, the loss of the chance to utilize by-products in the form of energy recovery, and the higher amount of waste collection and transportation.

Under the different proportions of food and garden waste, anaerobic digestion and composting were shown to be suitable technologies for treating food waste and garden waste in centralized waste management systems, respectively. As for the on-site waste treatment systems, home composting was the appropriate technology to treat both food waste and garden waste.

According to the results and sensitivity analysis, the environmental impacts during the collection and transportation stages can be minimized by reducing the amount of waste sent to be treated by centralized systems by increasing the amount of waste treated by the on-site systems. Furthermore, we can reduce the waste collection distance by setting up a garbage collection point in a small community instead of collecting from each house. The main contributors to the anaerobic digestion of food waste were electricity and calcium hydroxide ($Ca (OH)_2$). The major contributors were the direct emissions from the garden waste composting and home composting. Garden waste (wood) incineration is also heavily reliant on electricity. As a result, reducing direct emissions from both garden waste composting and home composting can reduce around 6% of the total impact by controlling operation conditions. The implementation of on-site waste treatment technologies can reduce the impacts of collection and transportation stages. For example, the impact of photochemical oxidant formation can be reduced by around 10% for 100 kg of organic waste treated by an on-site system. Utilization of the by-products was the primary means of reducing the total environmental impacts. Furthermore, increasing the efficiency of the production of by-products by increasing the energy recovery efficiency of waste to energy systems and compost can offset more environmental impacts.

This study can potentially provide useful information on integrated municipal organic waste management systems for researchers, central and local stakeholders, and policymakers. This study could be applied to local municipal organic waste management systems in areas with similar conditions or adapted to other possible alternative technologies for the Thai context in the future. In addition, the results of this research can be used as guidance for developing countries with conditions and a composition of municipal organic waste similar to Thailand for making initial decisions. To make it more appropriate for the situations in each country, this might need additional adaptation.

To provide a more comprehensive and accurate assessment of the future of municipal organic waste management in Thailand, the following factors should be considered: updating the waste fraction and component of each type of waste in Thailand; developing and applying Thai-specific emission factors for emission modelling in Thailand; taking into account other impact categories such as land transformation and particulate matter formation; estimating losses at waste collection or commingled with other types of waste; including more possible treatment technology and by-product utilization strategies; and evaluating life cycle costing and eco-efficiency to improve decision making.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su15010090/s1. S1 Emission factors for organic waste (food waste and garden waste) management technologies at treatment stage. Table S1.1: Emission factors for organic waste (food waste and garden waste) management technologies at treatment stage. S2 Emission factors for organic waste (food waste and garden waste) management technologies at by-product utilization stage. Table S2.1: Emission factors for organic waste (food waste and garden waste) management technologies at by-product utilization stage. S3 Municipal organic waste energy content calculation. Table S3.1: Waste energy content calculation. S4 Life Cycle Inventory (LCI) results of a centralized food waste composting system. Table S4.1: Life cycle inventory results of centralized food waste composting system. Table S4.2: Food waste characteristics. Table S4.3: Nitrogen balance. Table S4.4 Phosphorus balance. Table S4.5: Potassium balance. Table S4.6: Energy balance. Table S4.7 Nutrient content of compost S5 Life Cycle Inventory (LCI) results of a centralized food waste anaerobic digestion system. Table S5.1: Life Cycle Inventory (LCI) results of centralized food waste anaerobic digestion system. Table S5.2: Food waste characteristics. Table S5.3: Nitrogen balance. Table S5.4: Phosphorus balance. Table S5.5: Potassium balance. Table S5.6: Energy balance. Table S5.7 Nutrient content of compost. S6 Life Cycle Inventory (LCI) results of food waste processor (on-site system) Table S6.1: Life Cycle Inventory (LCI) results of food waste processor (on-site system). Table S6.2: Food waste characteristics. Table S6.3: Nitrogen balance. Table S6.4: Phosphorus balance. Table S6.5: Potassium balance. Table S6.6: Energy balance. Table S6.7 Nutrient content of compost. S7 Life Cycle Inventory (LCI) results of a centralized garden waste composting system. Table S7.1: Life Cycle Inventory (LCI) results of centralized garden waste composting system. Table S7.2: Garden waste characteristics. Table S7.3: Nitrogen balance. Table S7.4: Phosphorus balance. Table S7.5: Potassium balance. Table S7.6: Energy balance. Table S7.7 Nutrient content of compost. S8 Life Cycle Inventory (LCI) results of a centralized garden waste incineration system (Wood). Table S8.1: Life Cycle Inventory (LCI) results of a centralized garden waste incineration system (Wood). Table S8.2: Garden waste characteristics. Table S8.3: Nitrogen balance. Table S8.4: Phosphorus balance. Table S8.5: Potassium balance. Table S8.6 Energy balance. S9 Life Cycle Inventory (LCI) results of landfill system (Wood). Table S9.1: Life Cycle Inventory (LCI) results of landfill system (Wood). Table S9.2: Garden waste characteristics. Table S9.3: Nitrogen balance. Table S9.4: Phosphorus balance. Table S9.5: Potassium balance. Table S9.6: Energy balance. S10 Life Cycle Inventory (LCI) results of composting bin (on-site system). Table S10.1: Life Cycle Inventory (LCI) results of composting bin (on-site system). Table S10.2: Garden waste characteristics. Table S10.3: Nitrogen balance. Table S10.4: Phosphorus balance. Table S10.5: Potassium balance. Table S10.6: Energy balance. Table S10.7 Nutrient content of compost. S11 Life Cycle Inventory (LCI) results of home composting (on-site system). Table S11.1: Life Cycle Inventory (LCI) results of home composting (on-site system). Table S11.2: Garden waste characteristics. Table S11.3: Nitrogen balance. Table S11.4: Phosphorus balance. Table S11.5: Potassium balance. Table S11.6: Energy balance. Table S11.7 Nutrient content of compost. S12 Nutrient and energy balance. Table S12.1: Nitrogen balance. Table S12.2: Phosphorus balance. Table S12.3: Potassium balance. Table S12.4: Energy balance. Refs. [10,15,18,24,31,36–43,48,49,56,57] are cited on the supplementary materials.

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