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Development of Sustainability Assessment Criteria in Selection of Municipal Solid Waste Treatment Technology in Developing Countries: A Case of Ho Chi Minh City, Vietnam

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Abstract: Municipal solid waste (MSW) management is a significant problem for developing countries due to lack of sufficient infrastructure, poor management capacity, and low level of waste treatment technology. This study proposes three main groups of criteria, i.e., social, economic, and environmental, that can be used as an effective tool to assess the sustainability of MSW treatment technologies, considering Ho Chi Minh City, Vietnam as a case study. The sustainability assessment criteria consist of a list of indicators which consider potential waste treatment plants. The indicators and technologies then undertake a selection process from identifying assessment goals and key aspects to data collection and consultation of experts. The findings from the previous phase will be used to select the most preferred waste technology through AHP and normalization approaches. As a result, 12 selected indicators are as follows: investment cost, treatment cost, operation and maintenance costs, revenue/benefits, job creation, community consensus, support policy, community health, air pollution, water pollution, greenhouse gas emissions, and land quota. Among three MSW facilities selected, i.e., landfill, compost, and waste-to-energy incineration, waste-to-energy is determined as the best alternative solution for Ho Chi Minh City in a given context of approximate 70% of landfilling being applied. The selection process and indicators found can guide decision-makers and policy on selecting MSW treatment technologies in developing countries. Additionally, Ho Chi Minh City's governors benefit from finding the most appropriate waste technology. A technology adoption roadmap and its implementation plan should be thought thoroughly to address challenges in MSW management in the city.

Keywords: sustainability assessment criteria; municipal solid waste treatment technology; analytic hierarchy process; expert survey; feature scaling; megacity

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1. Introduction

The management of municipal solid waste (MSW) is becoming increasingly significant in developing countries due to their rapid economic growth and high consumption rates [1]. The increase in population, together with the improvement in people's living standards, inevitably leads to an increase in the volume of solid waste, placing great pressure on environmental protection as well as environmental remediation activities [2,3]. Every year, the earth will receive two billion tons of MSW, equivalent to a volume of 300 kg/person/year. By 2050, the volume of global solid waste is expected to reach 3.4 billion tonnes per year [4]. One of the biggest challenges for developing countries to manage the MSW, especially in megacities in the Asia-Pacific region, is the waste ending up at landfills at an increasing alarming rate [5]. The combination of inadequate waste management capacity and the lack of sorting at source has led to environmental pollution, including ocean pollution and the blocking of sewers [6], which in turn has resulted in the spread of diseases [7] and negative impacts on economic growth, such as limiting the potential for tourism development [4,8].

Currently, solid waste treatment technology is diverse, such as anaerobic landfill with or without gas recovery, semi-aerobic landfill [9–11], composting [12], incineration with and without energy recovery, production of solid fuels, and pyrolysis [13,14]. Energy recovery from waste incineration for electricity plants is a promising technology, especially for developing countries, to turn waste into a usable form of energy [13]. Some literature has listed the advantage and disadvantage of technologies for MSW management, such as [15–17]. For instance, landfilling is considered as a relatively low-cost method, yet it requires a large area of land. Composting is likely to produce organic fertilizer but should be reducing waste size and effectively separating waste material input to attain high-quality products. Incineration is an advanced method with high capital, operational, and maintenance costs, and requires experienced operators. However, the method is an optimal land usage solution and is able to reduce up to 90% of disposal waste volume in landfills [15].

Moreover, the selection of treatment technology for each locality will depend on the assessment of pros and cons of each technology, coupled with the site area, operation techniques, and economic and environmental factors. Typically, the MSW composition percentage of organic solid waste in a study in Sepang City, Malaysia was 73.2%, with high moisture content. The authors suggested that a combination of treatment technologies, including recycling, composting, and incineration is the best and suitable alternative solution [18]. Additionally, inspired by MSW being considered as one of the renewable energy sources in Thailand, Sun et al. [19] proposed two integrated solutions for sustainable MSW management in Bangkok: composting and gasification in case of having market opportunities for compost products, and anaerobic and gaseous decomposition once biogas production and power generation play a more important role. The biggest component of MSW composition in the Philippines is organic waste and metal, hence waste processing with refuse-derived Fuel (RDF) to produce fuel has been practiced [20]. Meanwhile, the primary MSW management strategy in Malaysia is an integration of waste-to-energy processing, recycling, composting, and bio gasification [21].

On the other hand, to evaluate the selection of waste treatment systems regarding sustainability concepts, a number of studies rely on solid waste assessment criteria, particularly in developing countries [22]. For instance, a study assessed the sustainability of solid waste management in India through their own developed indicators. A total of 13 indicators were categorized into four areas: economy, society, environment, and governance [23]. In Thailand, a small city considered the criteria of environmental (with 3 indicators), economic (3), social (2), and technical (4) dimensions when conducting the assessment of the solid waste management system. The results showed that the environmental aspect is considered as the most important [24]. In addition, to develop a set of criteria for sustainable solid waste management in Central Java Province, Indonesia, the authors selected 12 criteria and 3 alternative treatment solutions (composting, recycling, and sanitary landfill) [25]. However, the aforementioned studies have some limitations. First, the evaluation of selection criteria is not comprehensive, especially regarding the lack of in-depth analysis of the participants' responses. Second, the expert survey approach is limited by their expertise and organized in the form of separate seminars. Third, although the selection criteria for MSW treatment technology involves technical domains, its indicators should be clarified for operational activities (e.g., cost, level of technology) and continuously updated along with the evolution of innovation and new technology. A waste treatment system is feasible if it is economically and technically sound, reliable, easily manageable, and involves community engagement [26].

In addition, several methods have been applied for selecting optimal alternative treatment solutions. The Analytic Hierarchy Process (AHP) method was used to determine weights of criteria and find alternative treatment solutions [24,27–30], whereas the TOPSIS method was adopted to propose a suitable waste treatment in Lahore [31]. The AHP method was also incorporated into the Delphi method to identify a proper set of criteria and technologies to treat MSW that are more economical and environmentally sound [32]. Additionally, an expert survey associated with linear regression analysis was conducted to develop a set of criteria for MSW management in the coastal area of Northern Vietnam [33]. Similarly, a study in Tabriz, Iran employed the same method to compare different waste management strategies [34].

Ho Chi Minh City (HCMC) is one of the most dynamic and largest economic centers across Vietnam and the Southeast Asian region. Similar to other cities in developing countries, HCMC is facing the problem of solid waste due to population growth, urbanization, and economic growth, has one of the highest MSW rates in the country [35], and is the fastest growing city in Vietnam [36]. The average GDP per capita is expected to reach USD 8430–8822 by 2020 and USD 13,340–14,285 by 2025. Its economy is predicted to continue growing in the coming years, with a growth rate of 9.5–10.0% per year from 2016–2020 and 8.5–9.0% per year from 2021–2025. The city's economic structure is shifting towards services (54.8%), industry and construction (28.76%), and agriculture, forestry, and fisheries (0.84%) [35].

On the other hand, the amount of waste generated in the city is increasing annually, with an estimated amount of 9800 tons/day in 2020, expected to increase to 13,520 tons/day in 2050. The current waste treatment technologies are being applied, i.e., sanitary landfill (68.6%), composting (24.6%), recycling (1.1%), and incineration (5.7%) [37]. According to the Decision No. 1485/QD-TTg dated 6 November 2018, on approving the solid waste planning mission of Ho Chi Minh City to 2025 with a vision towards 2050, the proportion of landfilling technology must be less than 10%, while using waste-to-energy technology with energy recovery must be increased by 60–80%. The city's current MSW management treatment system ends up at two integrated solid waste treatment facilities: the Northwest Integrated Solid Waste Treatment Facility in Cu Chi District and the Da Phuoc Integrated Solid Waste Treatment Facility in Binh Chanh District [38]. The two landfill sites, Da Phuoc and Phuoc Hiep, are no longer able to cope with the current amount of MSW [37].

Briefly, the ultimate objective of the study is to identify the most suitable technology to appropriately manage the current waste crisis in line with sustainable development in Ho Chi Minh City. To attain this objective, sustainability assessment criteria are developed which include indicators aggregated into three main domains, i.e., social, economic, and environmental indexes, and prospective MSW treatment technologies. The indicators and technologies undertake a selection process from identifying assessment goals and key aspects to data collection and consultation of experts. The results of the previous step will be used to select the most preferred waste technology through AHP and normalization approaches. Overall, the current study seeks to answer the following questions:

1. What are the suitable and effective indicators for assessing the sustainability of MSW treatment technologies in Ho Chi Minh City?
2. What is the most appropriate MSW treatment technology to cope with the current waste crisis in the city?

The novelty of this study is as follows. It builds a sustainability assessment criteria framework based on empirical information. In addition, an expert survey method is adopted across different stages of the study. Finally, we suggest a detailed process of selecting indicators in the evaluation of the sustainability of MSW facilities. The selection process and indicators found are likely to assist decision-makers and policy planners seeking guidance on selecting MSW treatment technologies in developing countries. Moreover, Ho Chi Minh City's governors can benefit from determining the most appropriate waste technology. A technology adoption roadmap and its implementation plan should be thoroughly thought through to address challenges in MSW management in the city.

2. Materials and Methods

2.1. Data Sources

Regarding the database, we rely on public data sources to collect information: the annual report on the national state of environment of the Ministry of Natural Resources and Environment (MONRE), the report on the environmental state of Ho Chi Minh City Department of Natural Resources and Environment (HCMC DONRE) during the period 2010–2020, the environmental report of Ho Chi Minh Urban Environment Company Limited (CITENCO), provincial statistical yearbooks during 2019–2021 of Ho Chi Minh City, and relevant publications in literature. Furthermore, after finalizing indicators in the sustainability assessment criteria, the study collects information of the magnitude and the value of those indicators from waste processing facilities across Vietnam such as Da Phuoc Waste Treatment Complex, Nam Son Waste Treatment Complex, Can Tho Waste-to-Energy Plant, and Tam Sinh Nghia Investment Development JSC.

2.2. Waste Characteristics in the Study Area

The waste generation of the city is 0.81 kg/person/day, which is relatively consistent with the statistics from the World Bank's survey of 120 countries worldwide [35]. The waste characteristic fluctuates according to its socio-economic factors such as lifestyle, affluence, season, and cultural activities. Urban areas collect 95% of the total solid waste generated, whereas the remaining 5% arises from households that do not dispose of their waste directly to the waste collection units. Instead, they abandon it near public waste containers or dump it in the city's canals. In suburban areas, the rate of direct waste collection from households is around 70–80%, with 20–30% of the remaining waste being self-treated by burying waste in their gardens or dumping it in vacant landfills.

The quantity of MSW of the city on a daily basis and annually from 2010 to 2020 is shown in Table 1. Overall, the waste generation rate is gradually increasing by 3–8% per year. Between 2017 and 2020, the rapid increase in waste generation can be attributed to multiple factors. First, the economic growth of the city and the increase in average per capita income [39] lead to the overconsumption of goods and services, resulting in a corresponding increase in municipal solid waste generation [3,39]. Second, urbanization combined with population growth have created densely populated areas such as residential buildings, commercial centers, offices, and industrial zones which require more goods and services, thereby leading to an increase in MSW. Third, the behaviors of waste reduction, reuse, and recycling have not been thoroughly ingrained in many places, which is also a significant factor affecting the increase in MSW in HCMC [40].

Table 1. Amount of MSW generation in Ho Chi Minh City between 2010 and 2020.

Year	MSW Generation	
	Daily Amount (Tonne)	Annual Amount (Tonne)
2010	6241	2,277,961
2011	6423	2,344,445
2012	6472	2,362,419
2013	6700	2,445,500
2014	6900	2,518,500
2015	7064	2,578,500
2016	7288	2,660,273
2017	8300	3,029,500
2018	8700	3,175,500
2019	9200	3,358,000
2020	9800	3,577,000

(Source: Authors' elaboration, compiled from HCMC DONRE [37]).

The MSW composition in the study area is presented in Table 2. Organic waste with a high potential for biodegradation (61.25%) can be processed through composting and anaerobic digestion technologies. Waste segregation at the source plays a crucial role in ensuring the quality of compost meets standards [41]. Recyclable waste (31.6%) includes paper, plastic, glass, and metal, and the remaining waste (7.15%) can be recycled to create new products. The remaining waste will be suitable for incineration with or without energy recovery or refuse-derived fuel technology (RDF), and finally sanitary landfilling.

Table 2. Percentage of each MSW composition in Ho Chi Minh City.

Waste Composition	Percentage
Degradable waste	
Leftover food, vegetable peels, leaves, straw	**61.25**
Waste recycling and reuse	**31.60**
Paperboard	8.45
Plastics, plastics (plastic bottles, plastic bags)	12.35
Glass (bottles, broken cups)	6.55
Metals	4.25
Remaining waste	
Fabrics of all kinds, cotton wool, crockery, coal slag, fertilizer packaging	**7.15**
Total	**100.00**

(Source: HCMC DONRE [37]).

2.3. Selection Process of Sustainability Assessment Criteria in MSW Management

The criteria selection process begins with assessment goal definition, see Figure 1. In the research context, criteria are developed to evaluate the sustainability of MSW treatment plants based on three aspects of economy, society, and environment. From the literature review, the authors propose key aspects which should be considerate for city planners, including the following: sustainable MSW management; institutions, policies, and community engagement; MSW treatment technologies; and technology benchmarking. The issue of sustainable MSW management provides a foundation of concepts, principles, and aspects to achieve sustainability in the MSW management system. While institutions and policies reveal the legal dimensions related to MSW processing facilities, community engagement expresses their opinions on environmental and social matters. In addition, treatment technology exploration helps to understand its specifications, implementation requirements, pros and cons, estimation costs, as well as the feasibility of treatment technologies in reducing the impact on the environment and improving the quality of life for the community. Finally, a technology benchmarking process is also crucial for decision-makers when selecting MSW facilities. It enables planning to be evidence-based, particularly in specific areas located in a similar climate zone and equal to technology level of Ho Chi Minh City. In the next step, data collection from primary and secondary sources will be conducted in order to propose a draft of indicators and prospective technologies suitable for the city. The initial sustainability assessment criteria are presented in Table 3; they comprise 6 waste treatment technologies and 15 indicators. The draft is then finalized after expert interviews for the evaluation and modification of the proposed indicators, and utilized for further assessment when selecting appropriate treatment technology.

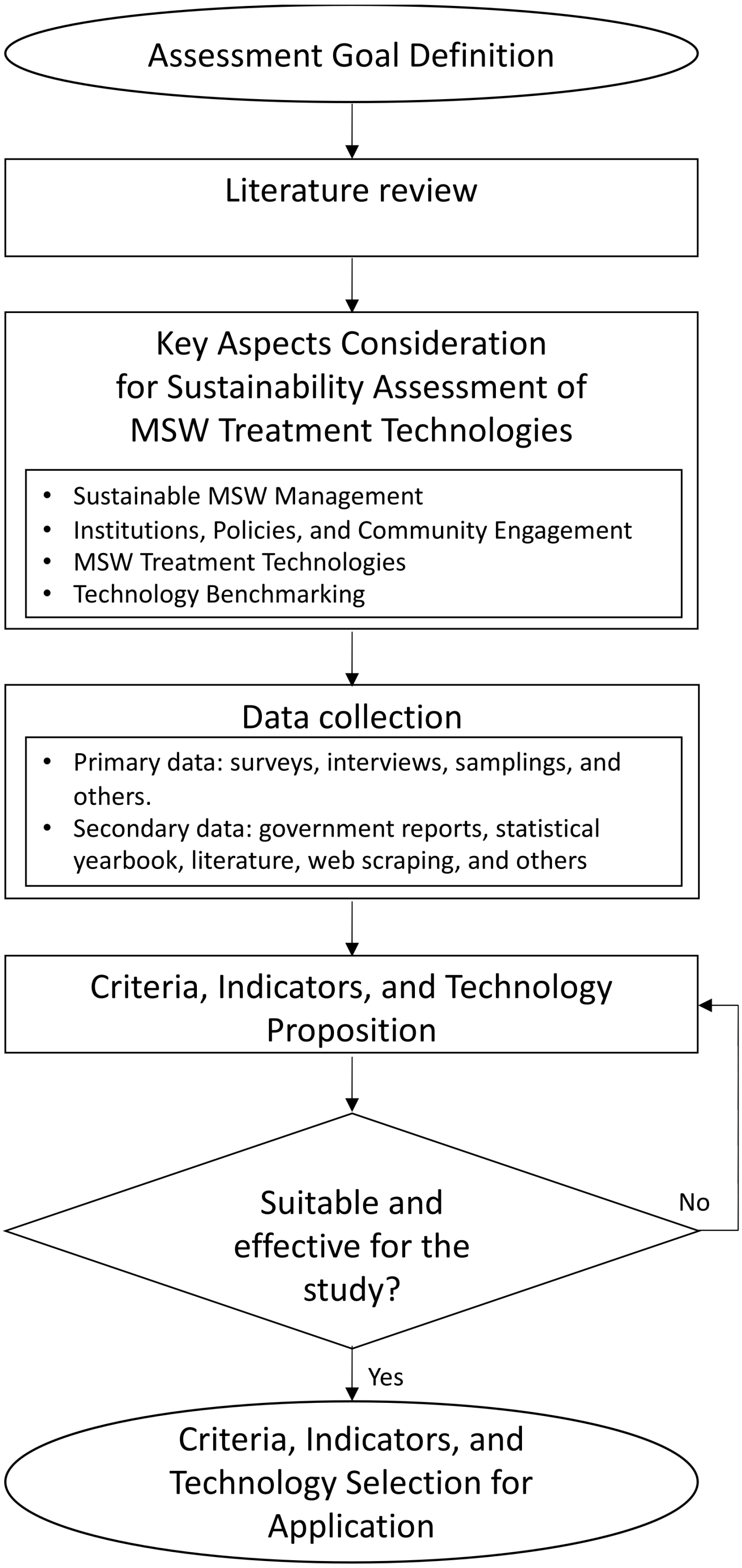

Figure 1. Selection process of indicators and criteria in MSW management.

Table 3. Proposed initial sustainability assessment criteria.

Technology	(1) Composing (2) Anaerobic decomposition (3) Recycling (4) Waste-to-energy (5) RDF—Energy Recovery Combustion (6) Landfilling	
Criteria	Indicator	Description
Economic	(1) Fixed cost	Investment costs for infrastructure and waste treatment.
	(2) Operating and maintenance costs	Maintenance and repair costs for equipment, machinery, and material costs.
	(3) Recruitment and training costs	The cost of recruitment and training for employee
	(4) Labor cost	This cost item is proposed for training human resources with the knowledge level to operate and control the treatment system.
	(5) Revenue/benefit	Selling electricity and compost.
Social	(1) Community culture	Community involvement in waste management.
	(2) Community's cooperation and awareness	Promoting the local community's acceptance of alternative waste treatment solutions that do not negatively impact quality of life or increase the number of lawsuits in the year.
	(3) Job creation	Creating employment opportunities for residents in the area where the waste treatment plant is located. The number of workers operating the equipment and their income level.
	(4) Community's health and safety	Number of people who lives nearby the waste treatment site having symptoms relevant to allergies, respiratory, and skin diseases.
	(5) Support policy	Price support policies for waste treatment, electricity sales support, and compost sales support price.
Environmental	(1) Air pollution (odors and pollutant) from treatment activities.	Air pollution from treatment activities causing odors and emissions.
	(2) Water pollution	From treatment activities that cause odors from wastewater (leaching in landfills, composting, and incineration plants).
	(3) Greenhouse gas emission	Amount of CO_2 per tonne of waste emitted into the atmosphere.
	(4) Energy recovery from the treatment system	Recovering energy from the treatment system.
	(5) Land quota	Land use quota for treatment activities.

2.4. Methods

2.4.1. Analytic Hierarchy Process Approach

One of the two approaches to evaluating the sustainability of MSW facilities for HCMC is the Analytic Hierarchy Process (AHP). The AHP was proposed by Thomas L. Saaty in the 1970s and is a common technique of the Multi-Criteria Decision-Making (MCDM) method. Some reasons for choosing the decision-making tool are as follows. AHP has been extensively applied in many fields, particularly in solid waste management [42,43] and the public sector [44], which are highly relevant to the study. In addition, the method is easy to use for decision-makers and urban planners who are likely to select a method based on their familiarity and accessible possibilities [42,45]. It uses a hierarchical structure to break down a decision problem into smaller and more manageable sub-problems. Moreover, AHP provides a systematic framework for organizing and structuring decision-making criteria, which can help decision-makers to better understand and communicate their decision-making process.

AHP quantifies weights for problems which are broken down into criteria, sub-criteria, and alternatives in a hierarchy of different levels. A quantitative comparison for elements at a given hierarchy level is calculated in pairs to determine relative preferences [46]. The intensity of the preference is based on Saaty's scale from 1 to 9. Before adopting the achieved weights, it is necessary to check the consistency of the expert's assessment through the Consistency Ratio (CR). A CR less than or equal to 10% is acceptable [47].

To determine the highest weight among MSW treatment technologies in terms of sustainability criteria, the study has considered the following steps:

- Step 1: Build a matrix to compare the importance of each pair between groups of economic, social, and environmental criteria to determine the weights of criteria.
- Step 2: Build a matrix to compare the importance of 12 indicators with economic, social, and environmental criteria to determine the local weights of indicators.
- Step 3: Calculate the global weight of criteria by multiplying the weight of the criteria, which is the result of Step 1, and the local weights of the indicator, which is the result of Step 2, to obtain the composite weights of criteria in the AHP method.
- Step 4: Finally, we estimate the composite weight of an individual treatment technology, which is representative of the order of priority for the selection of waste treatment technology, i.e., the higher the weights, the higher the priority. The composite weight is calculated by multiplying the weights of criteria obtained from Step 1 by the weight of each technology determined in Step 4. All the AHP calculation steps will be detailed in Appendix 1 of Supplementary Materials.

2.4.2. Normalization Approach

The normalization approach hereby is a combination of expert and community surveys and features the scaling method. First, the experts' opinions determine the magnitude and the value of indicators surveyed. Since indicators in the assessment criteria are measured in different units, we then normalize these indicators in the range of values from 1–5, with the highest score of 5 being the best choice and, on the contrary, 1 being the worst choice. After the normalization process, these indicators share a common value range, which makes it easier and more convenient when comparing them from different technologies.

The steps are as follows:

- Step 1: Assess the importance level of indicators for determining scores through a questionnaire. Each expert assigns a level of importance to a single indicator based on their expertise and experience.
- Step 2: Scale the feature range from 1 to 5.
- Step 3: Evaluate results for the criteria indexes using the following Formulas (1)–(3):

$$\text{Economic index}: \ I_{eco} = \frac{\sum_{i=1}^{4} I_i}{4} \quad (1)$$

$$\text{Social index}: \ I_{soc} = \frac{\sum_{i=5}^{8} I_i}{4} \quad (2)$$

$$\text{Environmental index}: \ I_{env} = \frac{\sum_{i=9}^{12} I_i}{4} \quad (3)$$

where I_{eco}, I_{soc}, and I_{env} are indexes of economy, society, and environment, respectively. The component indexes of economic, social, and environmental domain are estimated using the arithmetic mean formula, which means each indicator in a component index is equally important for sustainable development. The arithmetic mean calculation is suitable to calculate component indicators and composite indicators in sustainable development areas since it will equalize and offset the differences in the numerical values of the criteria, thereby giving the most representative value for the research problem [48].

- Step 4: Calculate the average sustainability index for each treatment technology based on the results obtained from Step 3. The sustainability index (I_{sus}) is a composite indicator including three component indexes, i.e., economic, social, and environmental. The calculation is presented in Formula (4).

$$I_{sus} = \frac{I_{eco} + I_{soc} + I_{env}}{3} \quad (4)$$

A comparative result from both approaches will be displayed for selecting the most appropriate MSW treatment technology in Ho Chi Minh City.

2.4.3. Community and Expert Surveys

To grasp the situation and relevant challenges with respect to waste management and treatment in the study area, we conducted field investigations and interviewed 420 households who suffer from operations of waste treatment facilities. The sample size was determined using Yamane's equation with a population of 2,559,817 [49].

In addition, we gathered different opinions of 20 experts, and then cross-checked the information in their responses. Overall, 20 experts were selected, whose expertise are in economic, social, environmental fields. The authors also conducted surveys of local agencies with experience in public management to collect information regarding the annual budget supporting solid waste management activities, and for selling electricity and compost generated from waste materials, as well as the number of lawsuits filed in a year. Our criteria for selecting experts are as follows: (1) For the economic criteria, the authors select experts with experience in finance, cost management, and economic analysis to provide assessments and cost estimates for various technologies; (2) For the social criteria, experts who are experienced in knowledge of social issues such as community health, vulnerable groups under waste crisis, and the benefits of stakeholders; and (3) For the environmental criteria, experts working on issues in environmental management and monitoring, risk management, and environmental impact assessment from waste technologies are chosen. In addition, participants' opinion should be objective, not be influenced by personal interests, leadership domination, or from any organizations/agencies.

After cross-checking the process, 11 valid responses were adopted for further analysis. The whole process of developing a set of criteria for evaluating the sustainability of MSW treatment technologies is shown in Figure 2.

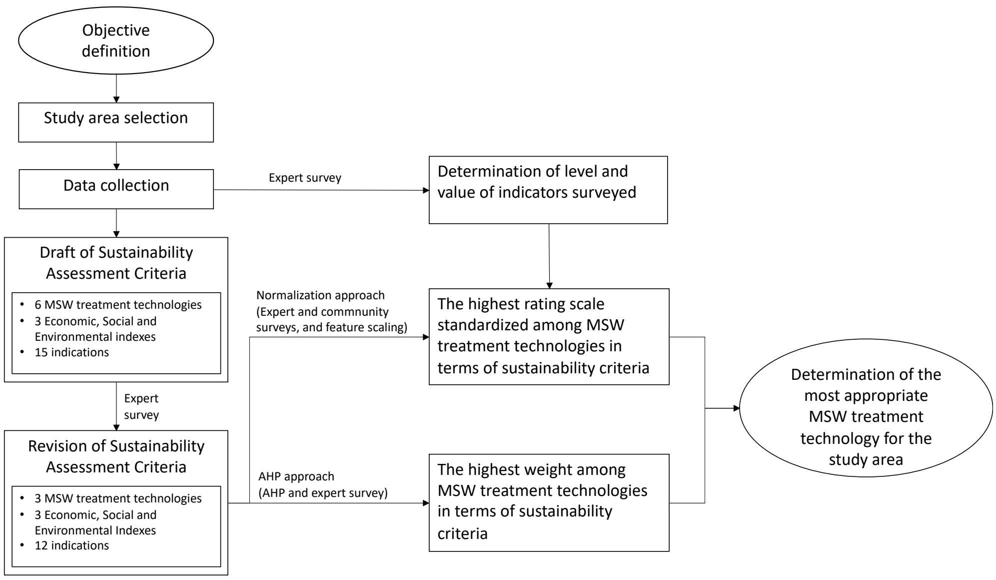

Figure 2. Overview of the research process.

3. Results and Discussion

3.1. Developing Sustainability Assessment Criteria

Table 4 provides the revision of the draft of sustainability assessment criteria with the support of a group of experts in various areas. From the 6 potential technologies (composing, anaerobic decomposition, recycling, waste-to-energy, and RDF) and 15 indicators in the main 3 sustainable domains (social, economic, and environmental), the assessment framework has been modified to become 3 technologies (landfilling, composting, and waste-to-energy), with 12 indicators of the 3 sustainable criteria.

Table 4. Revision of sustainability assessment criteria for MSW treatment technologies in Ho Chi Minh City.

Technology	Criteria	Indicator	Description	Unit
Landfilling Composting Waste-to-energy	Economic	1. Investment cost	Invest in infrastructure and equipment.	VND million
		2. Treatment cost	Unit price for waste treatment.	VND/tonne
		3. Operation and maintenance costs	Maintenance costs for equipment and machine, cost of purchasing raw materials.	VND million
		4. Revenue/Benefit	• Revenue from sales of electricity generated. • Revenue from sales of composting.	VND million VND million
	Social	5. Job creation	• Number of employees. • Income.	person/tonne VND million/month
		6. Community consensus	• Number of lawsuits in a given year.	number of cases/year
		7. Support policy	• Support policies for waste treatment. • Support policies for selling electricity and compost.	VND/tonne VND/tonne
		8. Community health	• Number of people who lives nearby the waste treatment site having symptoms relevant to allergies, respiratory, and skin diseases.	person/year
	Environmental	9. Air pollution	• NH_3 concentration. • H_2S concentration.	ppm ppm
		10. Water pollution	• BOD_5 concentration. • COD concentration.	mgO_2/L mgO_2/L
		11. Greenhouse gas emission	• Amount of greenhouse gas emissions into the atmosphere.	kg CO_2e/year
		12. Land quota	• Land use quota for treatment activities.	m^2/tonne

VND 1 million ~ USD 42.22.

Based on the sustainability assessment criteria determined in Table 4, the study applies AHP and normalization approaches to determine the highest scores among the three MSW treatment technologies.

3.2. Applying AHP Approach for Evaluating the Sustainability of MSW Treatment Technology

The criteria composite results are shown in Table 5. It is found that the environmental indicator (w_{env} = 0.370) plays the most important role in managing sustainable waste contrary to the social indicator (w_{soc} = 0.275), which has the least importance.

Table 5. Composite weight for the component criteria.

Criteria	Weights of Criteria (w_i)	Indicator	Local Weights of Indicator (w_j)	Composite Weights of Criteria ($W = w_i \times w_j$)
Economic	0.355	Investment cost	0.500	0.178
		Treatment cost	0.098	0.035
		Operation and maintenance costs	0.306	0.109
		Revenue/benefit	0.096	0.034
Social	0.275	Job creation	0.253	0.070
		Community consensus	0.257	0.071
		Support policy	0.162	0.045
		Community health	0.328	0.090
Environmental	0.370	Air pollution	0.513	0.190
		Water pollution	0.128	0.047
		Greenhouse gas emission	0.252	0.093
		Land quota	0.108	0.040

Among indicators of economic criteria, the two factors of investment cost (w_j = 0.500) and operation and maintenance costs (w_j = 0.306) have the most significant impact on the sustainability of MSW treatment technology. The findings also reveal that revenue in the economic domain in MSW treatment facilities is of less concern compared to a traditional business model that always prioritizes revenue or profit first. Given the rising waste in the city, the government and citizens desire sustainable technologies to treat the waste with reasonable cost at initiation and operational phases. Regarding the social aspect, there is not much difference among indicators. Community health (w_j = 0.328) is the biggest concern when operating the waste facility, followed by community consensus, job creation, and policy indicators. Clearly, health and participation of the community are factors that directly affect or are being affected during the establishment phase and operation of an MSW treatment project near their living environment. Finally, air pollution (w_j = 0.513) and greenhouse gas emission (w_j = 0.252) play the most important roles in MSW treatment technology with respect to environmental criteria. This means that the quality of exhaust gas from waste treatment systems should be managed well before being emitted into the environment.

Figure 3 describes composite weight of 12 indicators of the 3 criteria in descending order of the extent to which the indicators impact the sustainability of waste treatment technology in Ho Chi Minh City. The indicators of economic, social, environmental criteria are in red, yellow, and blue, respectively. Air pollution, investment cost, and operational and maintenance costs are the top three ranking of indicators with, their weight being 0.190, 0.178, and 0.109, respectively. These are also representative for top concerns of the local governor and community when deciding on MSW treatment technology. All weight calculations have CR < 10%, showing the consistency of experts' assessments. The results of all calculation process are presented in Tables S4–S7 of Supplementary Materials.

The finding results of composite weights of the three waste treatment facilities are shown in Table 6. Waste-to-energy technology (W = 0.514) has the largest weight, followed by composting (0.314), and landfilling (0.172). This indicates that waste-to-energy is the most preferred MSW treatment technology for the current state in the city. Composting is also an alternative of interest compared to landfilling technologies that are not an effective solution for the current MSW system in Ho Chi Minh City. The calculation of composite weight of three waste technologies will be detailed in Tables S8 and S9 of Supplementary Materials.

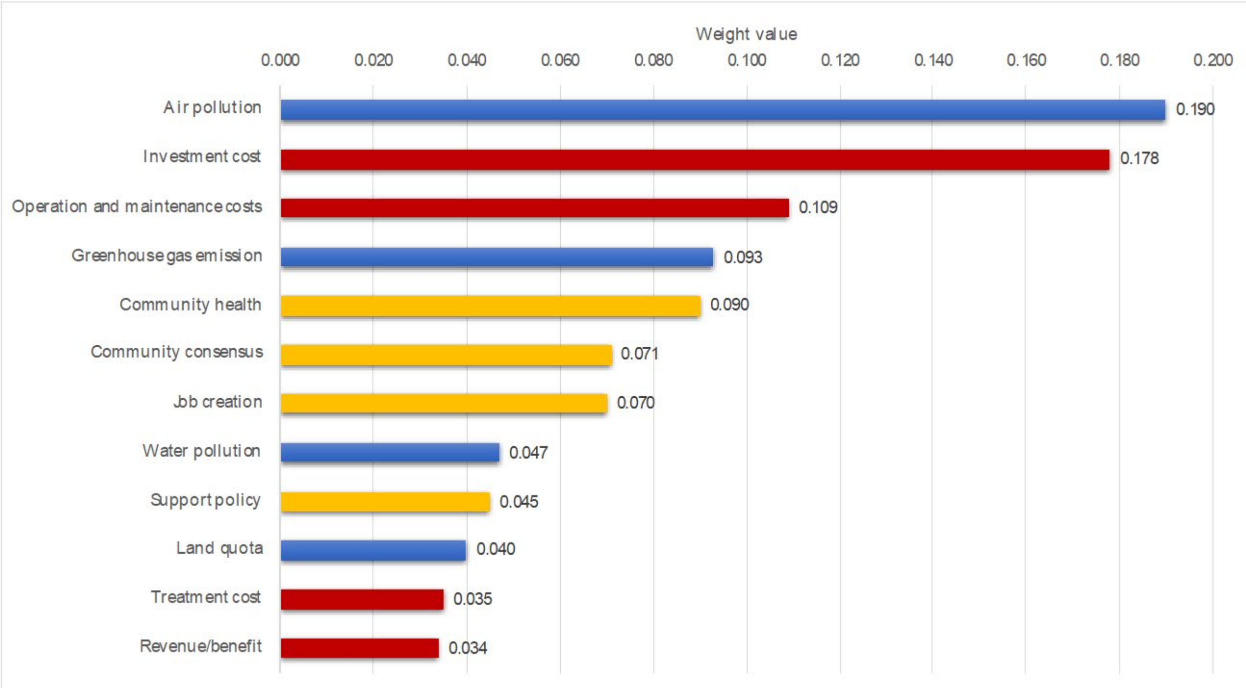

Figure 3. The impact of indicators on the sustainability of Ho Chi Minh City's waste treatment technology (environmental, economic, and social criteria are in blue, red, and yellow, respectively).

Table 6. Composite weights of three treatment technologies.

Criteria	Landfilling	Composting	Waste-to-Energy
Economic	0.105	0.058	0.191
Social	0.026	0.142	0.107
Environmental	0.041	0.114	0.215
Weight	0.172	0.314	0.514

3.3. Applying Normalization Approach for Evaluating the Sustainability of MSW Treatment Technology

Table 7 summarizes the empirical value of each indicator obtained through surveys regarding experts' opinions, local governors, and enterprises, together with corresponding evaluation points between 1 and 5 for the feature scaling process. Regarding indicators of economic criteria, generally, the higher the cost, the lower the evaluation point, and vice versa. Among the three technologies, waste-to-energy and composting have the larger amount of investment cost at the cost of less than 400 and more than VND 500 millions/tonne.day compared to less than 140 and more than VND 300 millions/tonne.day, respectively. These empirical values are greater than the regulation of Decision No. 1354/QD-BXD dated 29 December 2017 of the Ministry of Construction (hereafter Decision No. 1354) for MSW treatment technology by sanitary landfill, for example, with the capacity more than 800 tonnes/day at VND 140 millions/tonne.day, whereas according to the information collected from the Da Phuoc Integrated Solid Waste Treatment Facility (hereafter Da Phuoc Landfill), the investment cost for landfill is USD 107 millions, equal to VND 2538.6 billions, with a treatment capacity of 5000 tonnes/day, meaning the investment cost is greater than VND 300 millions/tonne.day. The situation is similar for treatment cost and operation and maintenance costs of the three MSW treatment technologies. For instance, Tran (2020) [50] claimed the treatment cost of Cau Dien Composting Plant is VND 500,000 per tonne with the treatment capacity of 137 tonnes/day. This cost is less than that regulated in Decision No. 1354 at VND 300,000–340,000 per tonne for a treatment capacity between 100 and 300 tonnes/day using foreign technology and equipment. In the case of the Vietstar Municipal Solid Waste Treatment Plant (hereafter Vietstar), which employs composting and recycling technology in Phase 1, with waste-to-energy technology in Phase 2 for MSW treatment, the company completed its first phase in 2021 with the treatment capacity of 1200 tonnes/day and the total treatment cost was VND 546,166 per tonne for whole waste processing. In terms of the operation and maintenance cost, the information collected regarding the cost is diverse based on the technology, management system, and the extent to which there are details regarding the cost component; hence, we use the same range in the three technologies. For instance, the maintenance cost for equipment at Nam Son landfill is VND 154.9 millions, and the raw materials cost (e.g., additives, probiotics) is VND 254 millions, as reported by Tran [50]. With regard to revenue/benefits from the sale of electricity and compost, we use a 5-point Likert scale for measuring because there is no waste-to-energy plant operating in Ho Chi Minh City and the compost produced is much smaller than the processing capacity due to inefficient waste segregation. Generally, the higher the revenue, the higher the rating point.

The study also uses a 5-point Likert scale from "extremely inadequate" to "substantial" for the number of employees indicator and "completely dissatisfied" to "completely satisfied" for the income indicator of social criteria in the three technologies when assessing the attitude of waste pickers. According to Da Phuoc, the average income of a worker is VND 5.7 million and they can earn an extra of VND 100,000–200,000 from selling recyclables. For the community consensus indicator, the authors survey 50 households living in the Nam Sai Gon urban area, Nhon Duc, Phuoc Kien, and Phuoc Loc Towns who are affected by activities of the Da Phuoc landfill, and 60% of which have a tick of lawsuits. To support MSW management, Ho Chi Minh City has policies to support waste treatment, e.g., payment of 369,706 per tonne for CITENCO VND, and payment of USD 21.1 per tonne for the Vietnam Waste Solution company (at Da Phuoc) in 2016, and approximately VND 550,000 per tonne in 2022. For power generation projects using MSW, the Prime Minister issued Decision No. 31/2014/QD-TTg dated 5 May 2014, with the support mechanism being VND 2114 per kWh (USD 10.05 cent per kWh) and VND 1532 per kWh (USD 7.28 cent per kWh) for directly incinerated and combusted gas collected from solid waste landfill, respectively. There is no specific policy supporting the selling of composting so far, hence we adopt a qualitative scale. To determine the rating scale of community health indicator, the study carried out a survey of 150 households in Phuoc Kien and Da Phuoc Towns. As a result, there were 590 cases in total with a pollution-related illness such as cough, sore throat, asthma, allergic rhinitis, skin diseases, and sore eyes; their level of impacts were based on the study [51].

With respect to environmental criteria, the range in H_2S and NH_3 concentrations in the air pollution indicator was based on the extent of human health impact, while the range in BOD_5 and COD concentrations in the water pollution indicator highly depended on the National Technical Regulation on wastewater of landfill QCVN 25:2009/BTNMT. Visvanathan et al. [52] characterized the leachate component of Pathumthani Landfill Site at Bangkok, Thailand showing 418 mg O_2/L of BOD and 4300 mgO_2/L of COD. The amount of greenhouse gas emission varies, depending on composition, MSW quantity, and the number of years of accumulation. Hoang (2013) [53] estimated the greenhouse gas emission of Nam Son landfill in 2011 was 2.23 million tonnes CO_2e, while Tran [50] claimed such an emission in 2020 was 1.15 million tonnes CO_2e; hence, we categorize the greenhouse gas emission in the range between 500 and 2000 thousand tonnes of CO_2e per year. Finally, the land use quota indicator is inspired by the land area of existing projects. The area of Nam Son landfill is 83 ha with an actual capacity of 4000 tonnes/day, while Da Phuoc landfill has 30.6 ha for landfill site and 5000 tonnes/day capacity. The composing site at Da Phuoc is 5.1 ha with actual capacity of 100 tonnes/day, and at Cau Dien is 3.9 ha with capacity of 134 tonnes/day. At Da Nang City solid waste treatment complex, the landfill site and composting site have the corresponding area of 500–900 m^2/tonne and 110–150 m^2/tonne. As for waste-to-energy technology, Can Tho's waste incineration plant with the capacity of

400 tonnes/day requires 1.44 ha, while Da Nang proposes the area of a waste-to-energy plant of 60–100 m^2/tonne.

Table 7. The level and empirical value of indicators by MSW treatment technology proposed.

Criteria	Indicator	Landfilling	Composting	Waste-to-Energy	Evaluation Point
Economic	1. Investment cost (VND million/ tonne.day)	>300	>550	>550	1
		>250–300	>500–550	>500–550	2
		>200–250	>450–500	>450–500	3
		>140–200	>400–450	>400–450	4
		≤140	≤400	≤400	5
	2. Treatment cost (VND/tonne)	>400,000	>500,000	>550,000	1
		>300,000–400,000	>400,000–500,000	>450,000–550,000	2
		>200,000–300,000	>300,000–400,000	>350,000–450,000	3
		>90,000–200,000	>250,000–300,000	>230,000–350,000	4
		≤90,000	≤250,000	≤230,000	5
	3. Operation and maintenance costs (VND million)	>550,000	>550,000	>550,000	1
		>450,000–550,000	>450,000–550,000	>450,000–550,000	2
		>350,000–450,000	>350,000–450,000	>350,000–450,000	3
		>230,000–350,000	>230,000–350,000	>230,000–350,000	4
		≤230,000	≤230,000	≤230,000	5
	4. Revenue/benefits—Electricity sales revenue (VND million)	Extremely low	Extremely low	Extremely low	1
		Low	Low	Low	2
		Moderate	Moderate	Moderate	3
		High	High	High	4
		Extremely high	Extremely high	Extremely high	5
	4. Revenue/benefits—Compost sales revenue (VND million)	Extremely low	Extremely low	Extremely low	1
		Low	Low	Low	2
		Moderate	Moderate	Moderate	3
		High	High	High	4
		Extremely high	Extremely high	Extremely high	5
Social	1. Job creation— Number of employees (persons/tonne)	Extremely inadequate	Extremely inadequate	Extremely inadequate	1
		Inadequate	Inadequate	Inadequate	2
		Moderate	Moderate	Moderate	3
		Adequate	Adequate	Adequate	4
		Substantial	Substantial	Substantial	5
	1. Job creation—Income (VND million/month)	Completely dissatisfied	Completely dissatisfied	Completely dissatisfied	1
		Dissatisfied	Dissatisfied	Dissatisfied	2
		Neutral	Neutral	Neutral	3
		Satisfied	Satisfied	Satisfied	4
		Completely satisfied	Completely satisfied	Completely satisfied	5
	2. Community consensus—Number of lawsuits in a given year (number of cases/year)	>50	>50	>50	1
		>30–40	>30–40	>30–40	2
		>20–30	>20–30	>20–30	3
		>10–20	>10–20	>10–20	4
		≤10	≤10	≤10	5
	3. Support policy—Support for waste treatment (VND/tonne)	≤230,000	-	-	1
		>230,000–350,000			2
		>350,000–450,000			3
		>450,000–550,000			4
		>550,000			5

Table 7. *Cont.*

Criteria	Indicator	Landfilling	Composting	Waste-to-Energy	Evaluation Point
	3. Support policy—Support for selling compost (VND/tonne)	-	Extremely low Low Moderate High Extremely high	-	1 2 3 4 5
	3. Support policy—Support for selling electricity (VND/tonne)	-	-	1000 1500 2000 2500 3000	1 2 3 4 5
	4. Community health—Number of people affected (persons/year)	>2000 >1500–2000 >1000–1500 >500–1000 ≤10–500	>2000 >1500–2000 >1000–1500 >500–1000 ≤10–500	>2000 >1500–2000 >1000–1500 >500–1000 ≤10–500	1 2 3 4 5
Environmental	1. Air pollution—H_2S concentration (ppm)	80–120 5–8 3 2–4 1–2	80–120 5–8 3 2–4 1–2	80–120 5–8 3 2–4 1–2	1 2 3 4 5
	1. Air pollution—NH_3 concentration (ppm)	5000–10,000 1720 700 400 37	5000–10,000 1720 700 400 37	5000–10,000 1720 700 400 37	1 2 3 4 5
	2. Water pollution—BOD_5 concentration (mgO_2/L)	>300 >200–300 >100–200 >50–100 ≤50	>300 >200–300 >100–200 >50–100 ≤50	>300 >200–300 >100–200 >50–100 ≤50	1 2 3 4 5
	2. Water pollution—COD concentration (mgO_2/L)	>3000 >2000–3000 >1000–2000 >300–1000 ≤300	>3000 >2000–3000 >1000–2000 >300–1000 ≤300	>3000 >2000–3000 >1000–2000 >300–1000 ≤300	1 2 3 4 5
	3. Greenhouse gas emissions (thousand tonnes of CO_2e/year)	>2000 <1500–2000 <1000–1500 <500–1000 <500	>2000 <1500–2000 <1000–1500 <500–1000 <500	>2000 <1500–2000 <1000–1500 <500–1000 <500	1 2 3 4 5
	4. Land quota (m^2/tonne)	>3000 <2000–3000 <1000–2000 <500–1000 ≤500	>170 <150–170 <130–150 <110–130 ≤110	>120 <100–120 <80–100 <60–80 ≤60	1 2 3 4 5

VND 1 million ~ USD 42.22.

Table 8 displays a list of evaluation points of each MSW treatment technology according to the scaling proposed. Regarding economic criteria, composting appears to be the lowest cost with the highest score in total (30.60), while both landfill and waste-to-energy obtain a 24.80 score. The highest evaluation point of composting results from the highest one in its component indicators including investment, treatment, and operation and maintenance costs. Comparing to landfilling technology's costs, waste-to-energy has a lower score, showing that waste-to-energy is the most capital-intensive. The findings of this study are in line with the report [54], which estimated the capital cost of incineration to be in the range of USD 190–1000 per annual tonne, and a study by Manaf [55] which argued that people were not in favor of incineration in part due to the high capital and installation and maintenance costs, and that this lead to public disagreement against waste incineration solutions. Tran [50] also claimed the high cost of Nam Son's waste-to-energy processing (VND 13,530.9 billion), compared to landfill (VND 6913.5 billion) and composting (VND 71.9 billion). On the contrary, the revenue from selling electricity is agreed upon by experts as obtaining a high score (39), whereas the revenue from selling composting products is not appreciated by experts. The possible explanation is a result of the aforementioned support mechanism policy of the Vietnamese government for energy-from-waste technology, and there has not been a policy for products from composting solutions. Overall, from an economic point of view, the preferred treatment method is composting. However, the method has limitations in practice such as the product consumption market, level of technology, capacity, and that leading to the current implementation is limited. For instance, Da Phuoc has the capacity of producing 100 tonnes/day of compost fertilizer, but in reality, it only achieves 10 tonnes/day. One of the main reasons for this is the low quality of the product due to the ineffective source separation from the commingled nature of MSW in Ho Chi Minh City [56].

Table 8. The total of evaluation points of component indicators by MSW treatment technology.

Indicator	Landfilling	Composting	Waste-to-Energy
1. Economic	24.80	30.60	24.80
1.1 Investment cost	26	38	23
1.2 Treatment cost	31	32	22
1.3 Operation and maintenance costs	31	35	19
1.4 Revenue/benefits			
+ Electricity	19	19	39
+ Compost	17	29	21
2. Social	25.86	31.33	38.33
2.1 Job creation			
+ Number of employees	40	28	41
+ Income	32	32	43
2.2 Community consensus	18	37	45
2.3 Support policy			
+ Support for waste treatment	31	31	26
+ Support selling compost, electricity	36	28	36
2.4 Community health	24	32	39
3. Environmental	21.67	29.33	42.33
3.1 Air pollution			
+ NH_3 concentration	24	37	46
+ H_2S concentration	17	28	43
3.2 Water pollution			
+ BOD_5 concentration	21	22	42
+ COD concentration	19	25	40
3.3 Greenhouse gas emissions	25	34	36
3.4 Land quota	24	30	47

As for social aspects, it can be seen that waste treatment using landfilling and waste-to-energy methods create more job opportunities for community. Additionally, workers working in waste-to-energy plants have a more competitive income. This may be due to the quality of service from the technology that has less impact on the environment and stable salaries for employees, compared to the remaining two technologies. Indeed, the waste-to-energy technology has also received the greatest score of community consensus and community health indicators, contrasting with the judgement in the study by Manaf [55].

On the other hand, working at landfills is also attractive to workers, particularly local workers. According to the survey of laborers working at Da Phuoc, although their income is not competitive, their jobs and incomes are quite stable for unqualified workers. The finding is consistent with Sun et al. [19] and Abba et al. [57], who reported that landfills create jobs for numerous local inhabitants, but that their life is very difficult. Policies that support waste treatment are not very different among the three methods, but polices supporting the selling of compost and electricity are dominated by landfilling and waste-to-energy; this is due to the potential of generating energy and electricity from these two technologies. Kling et al. [58] stated that, in developing countries, when converting treatment technologies from conventional landfill to incineration for power generation, there is support for generated electricity prices from the government (USD 25 per tonne of waste). In brief, incineration for electricity generation is currently considered to be the preferred alternative method in terms of social criteria. It benefits from the perception that energy can be used, and from saving land quota [5]. The trend is also consistent with Decision No. 491/QD-TTg on integrated solid waste management to 2025, with a vision to 2050 in the direction of considering solid waste as a resource, treating waste in combination with energy recovery, and reducing land use area in the context of its scarcity and rising cost in the city.

Akin to the social aspect, the results of environmental indicator criteria show the dominated evaluation points for waste-to-energy technology compared to the other two technologies, with a score greater than or equal to 40, except for the greenhouse gas emissions issue. It means waste-to-energy is considered as a method to create the least environmental impacts, whereas MSW landfill sites raise environmental concerns, particular in air and water pollution. Abba et al. [57] agreed with the statement for the case of MBT plants in Malaysia. When the incineration technology manages exhaust gas thoroughly, the possibility of odors and greenhouse gas emissions are much lower than that in landfill and composting. However, Zhao [59] supposed that if the incineration technology is not guaranteed, many different toxic wastes will be generated, such as CH_4, CO_2, and especially dioxins. This is one of the reasons why there is not much variation in scores for the three technologies regarding greenhouse gas emission in Table 8, and why the landfilling method obtains the lowest score, meaning the highest potential of greenhouse gas emission. This is consistent with the study [50] of the Nam Son landfill, and [57] of two landfills Seelong and Tanjung Langsat in Johor Bahru City, Malaysia. In brief, incineration is selected to be the optimal solution for generating electricity while protecting the environment.

From the results of the economic, social, and environmental components indicator shown in Table 8, the composite sustainability index is then calculated from Equations (2) and (4), presented in Table 9. Clearly, waste-to-energy ranks first due to the highest score obtained from the component indicators, followed by composting and landfilling.

Table 9. Sustainability composite indexes.

Criteria	Landfilling	Composting	Waste-to-Energy
Economic	24.80	30.60	24.80
Social	25.86	31.33	38.33
Environmental	21.67	29.33	42.33
Sustainability indexes	24.11	30.42	35.16

3.4. Selection of MSW Treatment Technology for Ho Chi Minh City

Table 10 summarizes the results from both approaches and their ranking accordingly. The higher the weight (for AHP method) or sustainability index score (for normalization method), the higher the ranking.

Table 10. Summary of MSW treatment technology selection by AHP and normalization approaches.

Technology	AHP Approach		Normalization Approach	
	Weight	Ranking	Sustainability Index Score	Ranking
Landfilling	0.172	3	24.11	3
Composting	0.314	2	30.42	2
Waste-to-energy	0.514	1	35.16	1

It can be seen that both AHP and normalization approaches achieve a similar ranking, in which waste-to-energy is the optimal selection, followed by composting and landfilling. The results are also consistent with previous studies that have chosen waste incineration with power generation as the solution in the context of lack of space for landfill and related environmental disadvantages [27,46,57]. This result is completely consistent with the research on urban solid waste management in ASEAN countries that has proposed the treatment technology of waste incineration to generate electricity for big cities. Moreover, this waste treatment method is also appropriate with the Solid Waste Management Plan of Ho Chi Minh City until 2025, with a vision towards 2050, which aims to limit landfill sites to less than 10%, and prioritize waste-to-energy incineration technology [37]. Recently, Decision No. 09/2021/QD-UBND of the People's Committee of Ho Chi Minh City dated 4 May 2021 regulated the waste segregation at source into two groups: waste that is reusable or recyclable, and other waste. This is one of the preparation steps for implementing incineration across the city in the near future. However, a combination of these technologies is recommended for the case of Ho Chi Minh, in which the waste increment rate is approximately 10% annually. This solution is also applied in some cities in countries including Malaysia [18], Thailand [19], and the Philippines [20], with technologies and climatic conditions similar to Ho Chi Minh City. Finally, each solid waste treatment technology has its own advantages and disadvantages appropriate for each type of waste composition, hence, the success of waste segregation at source programs in the city plays a key role for driving the success of waste treatment technologies.

4. Conclusions

The study builds a set of assessment criteria regarding sustainable development to determine the most appropriate technology for the current state of MSW management systems in Ho Chi Minh City. As a result, 12 indicators under the umbrella of economic, social, and environmental indexes are proposed for evaluating the sustainability of landfilling, composting, and waste-to-energy incineration technologies. These are investment cost, treatment cost, operation and maintenance costs, revenue/benefits, job creation, community consensus, support policy, community health, air pollution, water pollution, greenhouse gas emissions, and land quota. After finalizing the sustainability assessment criteria, AHP and normalization approaches are employed to identify the ranking of the three technologies to handle the MSW based on the defined framework. While composting is the most favorable technology in terms of economic aspect, incineration to generate electricity is the preferred method under social and environmental aspects. Both approaches achieve the same result, where waste-to-energy incineration ranks first, followed by composting and landfilling.

The sustainability assessment criteria are expected to be adopted in Vietnam and other cities of emerging economies that are struggling to manage the rising waste amount annually with a low level of waste treatment technology and a lack of sufficient infrastructure. The empirical values of the criteria framework from our surveys also contribute value information for academia and decision-makers to evaluate the MSW management in Vietnam in general and Ho Chi Minh City in particular. Although waste-to-energy incineration is the most appropriate technology for MSW treatment in Ho Chi Minh, the integration of the three treatment methods is recommended.

Nevertheless, some of information in the study is still limited, and values inspired from previous studies might not be suitable for Ho Chi Minh City. A further study should be conducted to clarify values of the indicators using methods of environmental impact assessment and environmental health impact assessment. Moreover, in order to effectively implement waste-to-energy incineration technology in Ho Chi Minh City, it is recommended to conduct studies on the mechanism for selling the generated electricity and connecting it to the national grid. This procedure is crucial in promoting investment and facilitating the application of advanced waste treatment technologies to address the waste crisis in the city center in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15107917/s1, Table S1: Score comparison of indicators; Table S2: Priority matrix of criteria; Table S3: Average random consistency index value; Table S4: Matrix calculation for comparing the level of importance among criteria groups; Table S5: Matrix calculation for comparing the importance level of economic criteria; Table S6: Matrix calculation for comparing the importance level of social criteria; Table S7: Matrix calculation for comparing the importance level of environmental criteria; Table S8: Matrix calculation for comparing MSW treatment technologies based on sustainability criteria; Table S9: Matrix calculation for pair-wise comparison of MSW treatment technologies based on sustainability criteria.

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