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ARTICLE

Sustainable food waste management using modified fuzzy improved analytic hierarchy process: a study of Malaysia

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Abstract

Food waste generation is a pressing issue that requires urgent attention and concerted efforts worldwide. The staggering amount of food wasted each year not only wastes valuable resources but also exacerbates environmental, economic, and social challenges. Food Waste Management (FWM) consists of a complex array of criteria and sub-criteria, and treatments which seems interdependent. There is a need to evaluate the FWM with the help of important criteria and sub-criteria and treatments to address this challenge. In this study, we identified four important criteria, 21 sub-criteria, and four alternatives of FWM for the case of Malaysia using the integrated approach of literature review and expert opinions. Further, we employed the approach of Modified Fuzzy Improved Analytical Hierarchy Process (IAHP) to corroborate the interrelationships among the identified criteria and sub-criteria, and their associated treatments. This study undertakes linear normalization methods to transform data into comparable numerical values and the Geometric Mean method to handle uncertainty in human judgments. Moreover, the Centroid method is employed to convert fuzzy weights into crisp sets for ease of interpretation. The results indicate that environmental is the most essential criterion, followed by social, economic, and technical. In addition, air and water pollution is identified as the most critical sub-criteria. Black Soldier Fly is discovered as the most sustainable FWM treatment, since it performs the best while meeting all the criteria and sub-criteria assessed. Sensitivity analysis demonstrates that the outputs from the proposed method are robust and reliable. The finding suggests a proper and robust approach to help decision-makers select suitable FWM treatments to tackle various criteria and alternatives especially when handling inconsistent and uncertain judgments during evaluation.

Keywords Multi-criteria decision-making · Sustainable food waste management · Improved Analytical Hierarchy Process · Fuzzy method · Sensitivity analysis

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Introduction

Food waste is one of the well-known and most challenging issues confronting the globe today. It refers to the materials made up for human consumption and eventually being discharged or lost by humans. Food loss, biowaste, kitchen waste, and food and drink waste are the terms used to define food waste. Approximately 931 million tons of food are wasted annually, with 61% coming from households, 26% from catering industries, and 13% from stores, according to the World Economic Forum [1]. The Food Waste Index Report 2021 from the United Nations Environment Program claimed that each Indian family member discards about 50 kg of food annually [2]. Consequently, reducing waste is advantageous for the environment, economy, and society. Since then, the United Nations Sustainable Development Goals have set a target of halving food waste by 2030.

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The significant growth of food waste creates major concerns in our society, including pollution, health risks, and the lack of dumping land [3]. Furthermore, food waste will cause higher interactions between wildlife, accelerating the transfer of illness and infections between animals and occasionally humans [4]. Apart from that, food waste has several socioeconomic repercussions that impact all of us. It damages the environment, worsens the climate crisis, depletes resources, and costs the global economy hundreds of billions of dollars annually [5].

Food Waste Management (FWM) refers to the process of reducing, recovering, and recycling food waste to minimize its negative environmental, social, and economic impacts [6]. It involves various strategies and practices aimed at preventing food waste generation, diverting it from landfills, and utilizing it in more sustainable ways. The goal of FWM is to maximize the value of food resources while minimizing waste. FWM encompasses a multifaceted framework of criteria, sub-criteria, and interconnected treatment methods. There are many criteria and sub-criteria of the FWM that are measured with treatment methods that are highly interdependent, making the performance measurement system of the FWM complex. The complexity is associated with (i) environmental impacts, (ii) consumer behavior, (iii) regulatory and policy challenges, and (iv) a lack of infrastructure and resources. Food waste contributes to various environmental issues, including greenhouse gas emissions, water and land resource depletion, and biodiversity loss [1]. Managing food waste in an environmentally sustainable manner requires considering these complex interconnections and adopting holistic approaches. Moreover, the generation of food waste can be attributed to consumers' insufficient awareness concerning effective food planning and management encompassing purchases, storage, preparation, and re-use [7]. This issue is rooted in time constraints, a lack of emphasis on developing waste reduction habits, and consumers' inadequate skills in storing and cooking food. To effectively address this problem, it is crucial to bring about a transformation in consumer attitudes and behaviors, placing significant importance on waste reduction practices.

The implementation of effective policies and regulations to tackle food waste is complex. It requires coordination among various stakeholders, including government bodies, industry associations, and non-profit organizations. Developing and enforcing regulations that incentivize waste reduction, facilitate food donation, and promote sustainable practices pose significant challenges. Moreover, the proper infrastructure and waste management systems are crucial for reducing food waste. However, in many regions, particularly in developing countries, such infrastructure is inadequate or non-existent. As an example, about 93 million small-scale farmers in Nigeria experience a 25% reduction in their yearly earnings because of food spoilage caused by the insufficient accessibility of cold storage infrastructure [8]. Limited resources and funding further hinder the development of comprehensive waste management systems. A gap exists when evaluating sustainable FWM performance, which is a complex and tedious task, as it involves diverse stakeholders with both common objectives as well as conflicting goals.

In Malaysia, about 50% of food waste is under municipal solid waste (MSW), and households are the primary source of MSW [9]. Malaysia wastes approximately 16,668 tons of food daily, equivalent to providing three meals to 2.2 million people [10]. Furthermore, 80% of all food waste in Malaysia is currently disposed of at landfills, which contributes to several impacts on the environment and society, such as threats to public health (i.e., diseases such as asthma and cancer), harm to ecosystems, and the environment (i.e., methane and greenhouse gas emissions) [11–13].

FWM is one of the categories of solid waste management under the Solid Waste and Public Cleansing Management Act 2007 (Act 672) in Malaysia [14, 15]. It can be any disposal form, including incineration, composting, landfilling, etc. There are a total of six FWM that are currently applied in Malaysia and other Asian countries, including (i) recycling, (ii) incineration, (iii) landfilling, (iv) composting, (v) anaerobic digestion, and (vi) animal feeding whereby composting, anaerobic digestion, and animal feeding are nature-friendly food waste handling methods [9, 14]. However, the success of FWM in Malaysia has been hindered by a lack of awareness and slow progress in implementing effective waste management practices [11]. Furthermore, landfilling is the current practice of handling food waste that is detrimental to the environment, society, and economy. Instead of landfilling, there are various preferable options for managing waste, such as composting and anaerobic digestion [16]. Local authorities of Malaysia opt for better waste management to replace it with the current practice. Therefore, it is crucial to identify a robust method for evaluating FWM performance for handling food waste issues in Malaysia.

This study aims to develop a sustainable FWM system that addresses all the important criteria and sub-criteria within the economic, environmental, social, and technical concerns. Specifically, this study aimed to identify the most cost-effective and environmentally friendly food waste treatment method for the case of Malaysia. Modified Fuzzy Improved Analytical Hierarchy Process (IAHP) is utilized to examine the current food waste treatment practices to achieve the goal, which can handle data transformations and uncertain judgment by the decision-makers. The criteria and sub-criteria for this study were identified through a literature review and further refined by the FWM experts. There are four criteria and 21 sub-criteria considered in the case study as follows:

i. Economic: Initial investment cost, collection and transportation cost, operational cost, revenue, and employment and job creation.
ii. Environmental: Air and water pollution, ecological impact, energy consumption, greenhouse gas emissions, and renewable energy.
iii. Social: Law and regulation, political support, public acceptance, health impacts, and smell impacts.
iv. Technical: Capacity, adaptability to system, land usage efficiency, technological maturity, efficiency, and reliability.

The following are the contributions to knowledge and application:

i. The novelty of this method lies in the new combination of (i) IAHP to determine the weight of criteria, sub-criteria, and alternatives of FWM, (ii) linear: max and linear: sum normalization method to transform data into numerical and comparable data with standardize beneficial and non-beneficial criteria, (iii) geometric mean method to handle the uncertainty involved in human judgments, and (iv) centroid method to convert fuzzy weight into crisp set which ease for interpretation.
ii. The Modified Fuzzy IAHP method was illustrated using a case study in Malaysia to provide the most suitable treatment to sustain FWM under multiple criteria views. There are four criteria, 21 sub-criteria, and four alternatives considered in the case study. Consequently, this study provides valuable insights and guidance for local authorities in improving FWM practices.
iii. In addition, this study demonstrates the potential of Modified Fuzzy IAHP to help address complex waste management challenges.

The summary of the rest paper is as follows: "Literature Review" offers a concise review of the criteria, sub-criteria, and alternatives of FWM. Additionally, it provides an in-depth examination of the study conducted to develop the Modified Fuzzy IAHP method. "Methodology" focuses on the development of the model, including its validation and the mathematical formulation utilized for the Modified Fuzzy IAHP method, and presents the study area of FWM in Malaysia. Moreover, "Results" demonstrates the application of the proposed method within the chosen study area and evaluates the performance of the output through sensitivity analysis. In addition, it includes a comparative study to assess the effectiveness of the proposed method. The "Discussion" section delves into a discussion of the findings, addressing various aspects related to criteria and alternatives considered in the study. The "Conclusion" section concludes the paper by providing a summary, highlighting its limitations, and offering recommendations for future research.

Literature review

FWM is a method used to handle food waste. In the multi-criteria decision-making (MCDM) context, FWM is viewed as an alternative option to achieve specific study goals. The concept of "alternatives" refers to the various options evaluated. Meanwhile, "criteria" represents the parameters used to assess and compare these alternatives. The selection of criteria must be independent of one another and measured on a consistent and quantifiable scale. Furthermore, within each criterion, there may be further breakdowns known as "sub-criteria", which delve into more detailed aspects of the specific criterion examined. The selection of the criteria and sub-criteria is crucial to having the correct parameter to assess the FWM performance. The inappropriate selection of these will lead to variance in the results and deliver the wrong decision to handle food waste issues.

Criteria of FWM

There are four main criteria in assessing the performance of FWM, including (i) environmental, (ii) economic, (iii) social, and (iv) technical [17, 18]. The criteria and sub-criteria considered by researchers in the FWM can be found in Table 1.

Environmental criterion is defined as the behavior of a waste management system toward the environmental element [17, 18]. From the environmental criterion perspective, the inclusive sub-criteria are (i) air and water pollution [19–21], which explains the impact of FWM alternative on air and water pollution, taking into account the gases and leachate produced, (ii) ecological impact [19], which refers to the effect of the FWM alternative on living creatures, such as people, plants, and animals, (iii) energy consumption [19, 23–25], which describes the amount of energy consumed by applications of each FWM alternative, (iv) greenhouse gas emissions [23, 24], which describes the volume of greenhouse gases emitted by each FWM alternative, and (v) renewable energy [20, 23], which indicates the energy regenerated by each FWM alternative. Air and water pollution, ecological impact, energy consumption, and greenhouse gas emissions are the sub-criteria that are supported by previous studies as one of the most important sub-criteria among the options considered from the studies [21, 23, 24, 26].

Economic criterion is defined as the behavior of a waste management system toward economic element [17, 18]. The sub-criteria considered under economic criteria includes (i) initial investment cost [19, 24, 26], which indicates the cost

Table 1 Criteria and sub-criteria of FWM

Criteria	Sub-criteria	Reference
Environmental	Air and water pollution	[19–22]
	Ecological impact	[19]
	Energy consumption	[19, 23–25]
	Greenhouse gas emissions	[23, 24]
	Renewable energy	[20, 22, 23]
Economic	Initial investment cost	[19, 24, 26]
	Collection and transportation cost	[19, 27]
	Operational cost	[19, 20, 24–26]
	Revenue	[20, 22, 23, 26]
	Employment and job creation	[20]
Social	Law and regulations	[19]
	Political support	[19]
	Public acceptance	[20, 22–24]
	Health impacts	[23]
	Smell impacts	[22–24]
	Noise impacts	[23, 24]
Technical	Capacity	[19, 22]
	Adaptability to system	[19, 20, 24]
	Land usage efficiency	[19]
	Technological maturity	[19, 27]
	Efficiency	[24, 25, 27]
	Reliability	[22, 25, 27]

FWM Food Waste Management

Table 2 Treatment on FWM

Alternative	Reference
Composting	[19, 20, 22, 24–28]
Anaerobic digestion	[19–23, 25, 27–29]
Landfilling	[19, 20, 25, 28]
Incineration	[19–21, 25]
Food waste disposal	[23, 27]
Ethanol fermentation	[21]
Pyrolysis and gasification	[21, 22]
Hydrothermal carbonization	[21]
Black soldier fly	[22]

of setting up FWM alternatives as well as the expenditures incurred during the opening of the disposal location, (ii) collection and transportation cost [19, 27], which refers to the expenses of waste collection and transportation to the FWM center, (iii) operational cost [19, 20, 24–26], which describes the expenditures associated with the FWM alternative and maintenance of equipment and technology regularly, (iv) revenue [20, 23, 26], which refers to the savings resulting from the use of renewable energy or materials, as well as the cost reduction from waste collection and transportation, and (v) employment and job creation [20], which explains how well the alternative in creating new opportunities for paid employment. Among the sub-criteria aforementioned, initial investment cost, operational cost, and employment and job creation are among the most important sub-criteria [23, 25, 26, 28].

Social criterion is defined as the behavior of a waste management system toward society element [17, 18]. From the social perspective, the inclusive sub-criteria are (i) law and regulations [19], which describes the rules and constraints that may affect the choice of FWM alternative, (ii) political support [19], which refers to the support from government or political organization for the FWM alternative, (iii) public acceptance [20, 23, 24], which refers to the degree of acceptance by the public for each treatment method used, (iv) health impacts [23], which describes the level of health impacts to the public for each treatment method used, (v) smell impacts [23, 24], which refers to the level of smell impacts to the public for each treatment method used, and (vi) noise impacts [23, 24], which describes the level of noise impacts to the public for each treatment method used. Law and regulations and smell impacts are the sub-criteria that supported by previous studies as one of the important sub-criteria among the options considered in the studies [19, 23, 24].

Technical criterion is defined as the behavior of a waste management system toward technical element [17, 18]. The sub-criteria considered under economic criteria includes (i) capacity [19], which describes the quantity of waste discarded in the facility, (ii) adaptability to system [19, 20, 24], which refers to the degree of compatibility that the FWM alternative has, (iii) land usage efficiency [19], which describes the degree of efficiency between the land used and the quantity of food waste treated, (iv) technological maturity [19, 27], which refers to the country's present technology level and capacity to combine with other FWM, (v) efficiency [24, 25, 27], which describes how efficiency the alternative is in regard to FWM, and (vi) reliability [25, 27], which explains the probability of an alternative operating without failure. None of the sub-criteria aforementioned were supported as the most important sub-criteria on the previous FWM studies.

Alternative of FWM

There are several FWMs considered by researchers to handle food waste issues, including (i) composting [19, 21, 28], (ii) anaerobic digestion [19, 20, 25],(iii) landfilling [19, 20, 28], (iv) incineration [19, 20, 25], (v) food waste disposal [23, 27], (vi) ethanol fermentation [21], (vii) pyrolysis and gasification [21], (viii) hydrothermal carbonization [21], and (ix) black soldier fly [22] as presented in Table 2.

Composting is also known as Aerobic Digestion. Composting is one of the most often utilized methods for dealing with food waste. Composting occurs when organic materials

are broken down by microorganisms, snails, insects, and earthworms in the presence of oxygen. Anaerobic digestion is a multi-step microbial process involving several metabolic processes. It converts food wastes to biogas and organic fertilizer by breaking down organic materials without the presence of oxygen. Methane is produced as a byproduct of the process and is one of the most potent renewable energy sources available. Landfilling is the deposition of food wastes in a certain area. It is the simplest way of handling food waste; however, it releases greenhouse gases that affect the environment negatively. Incineration is the technology that involves waste material combustion and converts the material into heat and energy. In most cases, the heat from combustion will be utilized by power steam turbines for energy generation. Another alternative is food waste disposal, where it is an electric device that is installed under the kitchen sink that grinds food waste before discharging it into the sewer for treatment at wastewater treatment plants. Next, ethanol fermentation is a process that produces ethanol from several types of food waste. Some notable food wastes utilized in bio-ethanol production include banana peel, pineapple waste, and sugar beet pulp. Pyrolysis and gasification are thermal processes that transform food waste into bio-oil, syngas, and biochar in an environment without oxygen. Gasification is a higher temperature version of pyrolysis. Hydrothermal carbonization is the wet process that transforms food waste into valuable resources (e.g., hydrochar and crude oil) using low temperatures and autogenous pressures.

Finally, black soldier fly is an emerging and promising biowaste treatment alternative that is attracting entrepreneurial activities all over the world, primarily because waste-fed larvae have the potential to be used as a starting material for a variety of commercial products, such as animal feed, biodiesel, and soil fertilizer [30, 31]. This technology can yield relevant value-added products commercially that can help build a circular economy by contributing to economically and environmentally sustainable waste management methods [31]. The core of the method relies on the Black Soldier Fly larvae that possess a remarkable appetite for organic matter, particularly food waste, including fruits, vegetables, grains, and even meat products. This unique trait makes them highly efficient decomposers of food waste using their strong mouth parts and powerful digestive enzymes, turning it into nutrient-rich frass and valuable biomass, such as oils and proteins [32]. The process begins with the introduction of food waste into a controlled environment conducive to the Black Soldier Fly's reproductive cycle. The life cycle of BSFL consists of five stages, including the eggs, larvae, prepupae, pupae, and adults [33]. Upon hatching, the eggs give rise to larvae that initiate the consumption of organic matter. This feeding process triggers a rapid and concurrent process of growth and development in the larvae, accompanied by the substantial consumption of waste materials. As the larvae continue to partake in the process, they undergo multiple exoskeleton shreds, facilitating a seamless and efficient decomposition process. The resulting excreted frass is endowed with a wealth of nutrients, making it an invaluable soil amendment that enhances soil quality and fosters robust plant growth.

MCDM of FWM

There are various analysis methods that have been used to examine the performance of FWM, including life cycle assessment [34], system dynamics [35], and MCDM [25]. Of all methods, MCDM plays an important role in evaluating and ranking the solution performance, where this method can handle problems involving multiple criteria and sub-criteria [36]. MCDM is a method to assist the decision-makers in choosing the best alternative from a group of feasible alternatives based on the study nature [37]. The fundamentals of MCDM process can be divided into a few stages which include (i) identifying the objective of the MCDM process, (ii) criteria selection, (iii) alternative selection, (iv) weighing method selection, and (v) aggregation [38].

Many existing MCDM methods are available in the literature, such as Analytic Hierarchy Process (AHP) [39], Elimination Et Choix Traduisant la Realité (ELECTRE) [40], Preference Organization Method Ranking for Enrichment Evaluations (PROMETHEE) [41], IAHP [42], and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [43]. AHP is found to be more compatible with waste management assessment standards and allows researchers to deal with numerous criteria and sub-criteria, such as environmental, economic and social factors [36]. Some success studies that using AHP methods in handling FWM problems are shown in [20, 25, 26]. However, the AHP model is prone to inconsistency issues whereby decision-makers may make inconsistent judgments as the number of criteria considered increases [42, 44]. This inconsistency arises when decision-makers make errors in assessing the importance of criteria. Moreover, information extraction and final judgments from the AHP model are also challenging [42, 45]. The interview sessions for this method are typically time-consuming, and decision-makers may provide misleading results due to exhaustion from the numerous questions posed.

The IAHP introduced by Li et al. [42] used sorting and ranking methods to mitigate AHP issues by improving the consistency ratio of the matrix. Furthermore, Li et al. [42] proposed an improved questionnaire to reduce the time-consuming and easy to extract the information during the interview session. The weight analysis presented in Li et al. [42] showed that the IAHP method has the same weights assigned as the AHP method in the comparison matrix and achieves the consistency requirement simultaneously. On the

other hand, the percentage of the IAHP comparison matrix that passes the consistency test simulated by MATLAB is a 100% pass rate for the number of criteria between three and nine, while AHP failed to pass when five criteria and above are considered. Some studies used the IAHP method as the weight assignation method [46, 47]. For instance, Zhang et al. [47] proposed the GIS-based spatial multi-index model where the IAHP method is utilized to sort the indicators according to their importance and assign the weight for each indicator based on the preference of the experts. It is found that the proposed model is robust and provides more accurate results for risk evaluation in terms of hazard, vulnerability, exposure risk indexes, and integrated flood risks.

Various IAHP have been introduced under the same name but different from the one introduced by Li et al. [42, 48–53]. However, this study focuses on improving the work by Li et al. [42] and note that the IAHP has never been tested to evaluate the FWM before. Some studies face difficulty in eliminating human judgment in the IAHP method and require a more comprehensive view to provide accurate evaluation [50, 53]. This is due to a lack of data transformation for numerical and data comparison. Thus, a data normalization method is required to compute and provide the ranking of the criteria and sub-criteria. Without data normalization on MCDM studies like AHP and IAHP, researchers will face difficulty in providing a standard scale for beneficial and non-beneficial criteria. Furthermore, uncertain judgment by the decision-makers may occur in the MCDM method which can lead to inaccurate decisions, resulting in the loss of core capabilities and exposure to unforeseen dangers which requires the fuzzification method, and the defuzzification method to be considered. Thus, to make a comprehensive evaluation method, the IAHP from Li et al. [42] is necessary to include the data normalization method, the fuzzification method, and the defuzzification method.

Data normalization is essential for MCDM problems to transform data into numerical and comparable data for ranking and rating the alternatives by providing a standard scale for the beneficial and non-beneficial criteria [36]. The linear normalization methods commonly used for the IAHP method are linear: max–min and linear: sum [48, 51, 53]. In addition, Vafaei et al. [54] analyzed and investigated the best normalization method for the AHP, which includes (i) linear: max, (ii) linear: max–min, (iii) linear: sum, (iv) vector normalization, and (v) logarithmic normalization. The study revealed that the best technique is integrating the linear: max and linear: sum normalization methods. Therefore, to ensure that the sum is 1, this study employs the combination method presented in Vafaei et al. [54].

The concept of fuzzy logic was initially proposed by Zadeh [55]. The theory of fuzzy sets has proven effective in situations where the facts are ambiguous or imprecise [56]. Fuzzy sets tackle these circumstances by assigning a membership degree to each object set through membership functions and fuzzy numbers. A fuzzy logic system consists of four key components, namely Fuzzification, Rules, Inference, and Defuzzification. Various membership functions have been introduced to handle imprecise information in the MCDM method, such as triangular, trapezoidal, sigmoid, and Gaussian functions [56]. Among these, triangular fuzzy numbers are more commonly used in practice due to their simplicity in calculation and suitability for defining work processed in fuzzy environment [57]. In this study, triangular fuzzy numbers are employed to define the rules and inferences for each entry from the IAHP method to the fuzzy weights, where it has been widely used in various MCDM studies, particularly in Fuzzy AHP method applications [58, 59]. The triangular fuzzy number structure is presented in the next section.

The fuzzification method was introduced to deal with the uncertainty due to the human subjectivity involved in the MCDM method, like AHP. Furthermore, fuzzification application in the MCDM method can generate more sensitive output by expressing the decision-makers' ideas in linguistic terms. Concerning the food waste context, the fuzzification method offers a strategic approach to addressing the issue of food waste segregation. This method effectively handles the complexity by defining linguistic variables that are distinct attributes of waste items. For instance, variables like "biodegradability" and "material type" can be intelligently converted into linguistic variables such as "high", "medium", and "low" through the deployment of appropriate membership functions. This approach enables a nuanced representation of food waste attributes, contributing to a more refined and accurate segregation process. There are three fuzzification methods commonly used in the AHP method, including (i) Geometric Mean Method [60], (ii) Logarithmic Least Squares Method [61], and (iii) Fuzzy Extent Analysis Method [62]. Of all fuzzification methods, Geometric Mean Method is chosen, because it is simple to adapt to fuzzy scenarios and ensures that a reciprocal comparison matrix has a unique solution. Furthermore, the IAHP method can mitigate the disadvantages of the method by providing perfect consistency in the comparison matrix.

The defuzzification method is the inverse version of the fuzzification method, in which a fuzzy set is converted into an appropriate crisp set [63]. Since fuzzy sets are partially sorted, direct comparisons can be difficult without ambiguity. Therefore, the use of defuzzification methods becomes necessary. There are several defuzzification methods, including (i) Max-membership principle, (ii) Centroid method, (iii) Weighted average method, (iv) Mean-max membership, (v) Centre of sums, and (vi) Center of largest area [64]. The Max-membership principle, Mean-max membership, and Centroid technique are the most widely used defuzzification methods [65, 66]. Among all defuzzification

methods, the Centroid method is selected and utilized in this study because it is commonly used as a defuzzification method. The mathematical formulation of the Modified Fuzzy IAHP method consists of proposed data normalization, fuzzification, and defuzzification methods, which are presented in the next section.

Methodology

This section provides discussions on the research methodology, which includes (i) model development, (ii) mathematical formulation, and (iii) an overview of the study area.

Model development

The Modified Fuzzy IAHP is developed by integrating the IAHP with linear: max and linear: sum normalization, Geometric Mean, and Centroid methods. It is worth noting that IAHP uses a discrete scoring scale from 1 to 10, which differs from the traditional AHP method. The example calculations presented below for Economic and Environment criteria, which use the highest and lowest assigned values and the algorithms proposed by Li et al. [42], demonstrate the maximum and minimum converted values and confirm that IAHP adheres to the nine scales method introduced by Saaty [39]:

Given that Economic has a value of 10 and Environmental has a value of 1, it is inferred that Economic is more important than Environmental. Thus, the weight assigned to Economic is

$a_{ij} = max(10-1,1)$

$a_{ij} = max(9,1)$

$a_{ij} = 9$

On the other hand, the weight assigned to Environmental as follows:

$a_{ij} = 1/(10-1)$

$a_{ij} = 1/9$

As demonstrated in the preceding example, the IAHP outputs conform to the nine-scale method and are identical to the linguistic terms in triangular fuzzy numbers, as outlined in the subsequent sub-section. The proposed method is well suited for this study because it can address MCDM issues that involve numerous criteria and sub-criteria, such as FWM problems. In addition, the proposed method tackles the challenge of providing a standard scale for beneficial and non-beneficial criteria using data normalization techniques while accounting for the uncertainty of decision-makers' judgments that can lead to inaccurate conclusions. Furthermore, it employs a defuzzification method to make the output comprehensible to non-mathematicians by presenting the results in crisp values rather than fuzzy numbers.

Figure 1 depicts the flowchart outlining the development of the Modified Fuzzy IAHP model. The process begins by organizing a comparison matrix based on the data gathered from the respondents. Subsequently, the consistency ratio is calculated using the IAHP method based on respondents' feedback concerning food waste treatment. The Geometric Mean method integrates all the respondents' feedback and copes with uncertainty to calculate weight assignments in a fuzzy set for criteria, sub-criteria, and alternatives, but only if the comparison matrix passes the consistency test. The fuzzy comparison matrix produced by the Geometric Mean method does not require an additional consistency test. As per the theorem established by Buckley [60]: If the comparison matrix from the crisp AHP is consistent, then the comparison matrix from the FAHP is also consistent.

Subsequently, the Centroid method is essential to obtain the crisp value from the fuzzy weight that helps the alternatives ranking purpose. Before calculating the alternative ranking, the data require transformation using the data normalization method recommended by Vafaei et al. [54]. These methods were employed to standardize the beneficial and

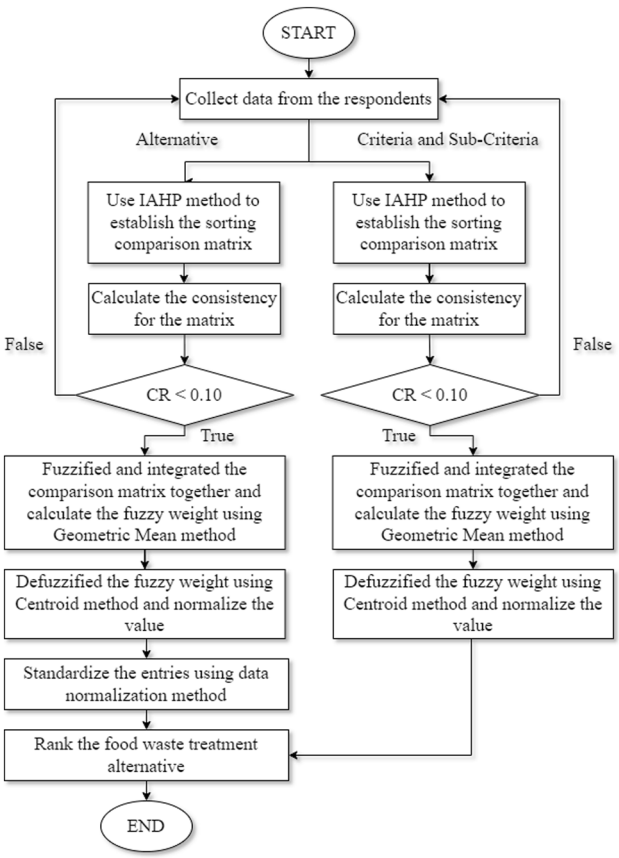


Fig. 1 Flowchart of modified fuzzy IAHP framework

non-beneficial criteria in the same comparison matrix. The final ranking for the alternatives is calculated by multiplying the alternatives' weights of the sub-criteria with the global preference weights (i.e., the multiplication between criteria weights with the sub-criteria weights).

Mathematical formulation

The following steps present the mathematical formulation for the Modified Fuzzy IAHP method to handle the MCDM issues.

1. Construct the sorting pairwise comparison matrix using the algorithms below [42]:
Let $\{B_i\}$ be a set of factors affecting decision A, where i=1, 2,…, n and n is the number of elements.
Order the factors B_i according to their importance using a discrete scoring scale from 1 to 10. There will be a set of scores $\{u_i\}$ where $i = 1, 2,\ldots, n$.
Construct the comparison matrix according to the ad-hoc rule:

i. If $u_i \geq u_j$, the matrix element $a_{ij}=max(u_i-u_j,1)$.
ii. If $u_i<u_j$, the matrix element $a_{ij}=1/(u_j-u_i)$.

The matrix A shown in Eq. 1 is the sorting comparison matrix where each entry of a_{ij} represents the importance of the i th criterion relative to the j th criterion

$$\mathrm{A} = \begin{bmatrix} a_{11} & \cdots & a_{1j} \\ \vdots & \ddots & \vdots \\ a_{i1} & \cdots & a_{ij} \end{bmatrix}, \tag{1}$$

i is the number of criteria considered in row, j is the number of criteria considered in column.

2. Calculate the geometric means of each row in matrix A using Eqs. 2, 3 to normalize the weights [67]

$$GM_i = \left\{a_{i1} \times a_{i2} \times \ldots \times a_{ij}\right\}^{1/n} \tag{2}$$

$$w_i = \frac{GM_i}{\sum_{j=1}^{j=n} GM_i}. \tag{3}$$

n is the number of criteria considered, GM_i is the geometric mean of criterion/sub-criterion i.

3. Equation 4 is used to form the n-dimensional column vector named as C matrix that represents the total of weighted values for the importance degrees of the respective criteria and sub-criteria.

$$\mathrm{C} = \mathrm{A} \times \mathrm{W} \tag{4}$$

$$W = \sum_{i=1}^{i=n} w_i$$

4. Find the consistency value of each row (CV_i) using Eq. 5 and using Eq. 6 to find the lambda maximum (λ_{max}) which indicates the average of the consistency value

$$CV_i = \frac{C_i}{w_i} \tag{5}$$

$$\lambda_{max} = \frac{\sum_{i=1}^{i=n} CV_i}{n}. \tag{6}$$

5. Calculate the consistency ratio using Eqs. 7–9

$$CR = \frac{CI}{RI} \tag{7}$$

$$CI = \frac{(\lambda_{max} - n)}{n-1} \tag{8}$$

$$RI = \frac{(1.987 * (n-2))}{n}, \tag{9}$$

CR is consistency ratio;
CI is consistency index;
RI is random inconsistency.

6. Set up the linguistic term as shown in Table 3 and Fig. 2 shows the membership function of triangular fuzzy number $\widetilde{A}$.

7. If the consistency ratio is less than 0.10, then form a new comparison matrix $\tilde{\mathrm{A}}^{\mathrm{k}}$ via fuzzy scale set up from step 6 as in Eq. (10) [68]

$$\tilde{\mathrm{A}}^{\mathrm{k}} = \begin{bmatrix} \tilde{a}_{11}^k & \cdots & \tilde{a}_{mn}^k \\ \vdots & \ddots & \vdots \\ \tilde{a}_{m1}^k & \cdots & \tilde{a}_{mn}^k \end{bmatrix}, \tag{10}$$

k, number of decision-makers;
m, number of rows;
n, number of columns.
$\tilde{a}_{ij}^k = \left(l_{ij}^k, m_{ij}^k, u_{ij}^k\right)$, where l_{ij}^k is lower limit, m_{ij}^k is the peak and u_{ij}^k is the upper limit of the decision-maker k triangular fuzzy number.

8. Equation 11 was used to integrate all the decision-makers' feedback or preferences by averaging them into a new comparison matrix Ã as per the matrix below

$$\tilde{a}_{ij} = \frac{\sum_{k=1}^{K} a_{ij}^{k}}{K} \tag{11}$$

$$\tilde{\mathrm{A}} = \begin{bmatrix} \tilde{a}_{11} & \cdots & \tilde{a}_{1j} \\ \vdots & \ddots & \vdots \\ \tilde{a}_{i1} & \cdots & \tilde{a}_{ij} \end{bmatrix},$$

$\tilde{a}_{ij}=\left(l_{ij}, m_{ij}, u_{ij}\right)$, where l_{ij} is lower limit, m_{ij} is the peak, and u_{ij} is the upper value of the triangular fuzzy number.

9. Calculate the geometric mean for each criterion using Eq. 12

$$\tilde{z}_i = \left\{\tilde{a}_{i1} \times \tilde{a}_{i2} \times \ldots \times \tilde{a}_{ij}\right\}^{1/n}. \tag{12}$$

10. Equation 13 was used to calculate the fuzzy weights ($\tilde{w}_i$) of each criterion finding vector summation of each $\tilde{z}_i$, acquiring (−1) power of summation vector and replacing in an increasing order, and finally multiplying $\tilde{z}_i$ with reverse vector

$$\tilde{w}_i = \frac{\tilde{z}_i}{\sum_{j=1}^{j=n} \tilde{z}_i} = \left(l_i, m_i, u_i\right), \tag{13}$$

$\tilde{w}_i=\left(l_i, m_i, u_i\right)$, where l_i is lower limit, m_i is the peak and u_i is the upper value of the fuzzy weights.

Table 3 Linguistic term for the comparison matrix of each criterion

Saaty's scale relative importance	Linguistic term	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
9	Extremely strong	(9,9,9)	(1/9,1/9,1/9)
8	Intermediate	(7,8,9)	(1/9, 1/8, 1/7)
7	Very strong	(6,7,8)	(1/8, 1/7, 1/6)
6	Intermediate	(5,6,7)	(1/7, 1/6, 1/5)
5	Strong	(4,5,6)	(1/6, 1/5, 1/4)
4	Intermediate	(3,4,5)	(1/5, 1/4, 1/3)
3	Moderately strong	(2,3,4)	(1/4, 1/3, 1/2)
2	Intermediate	(1,2,3)	(1/3, 1/2, 1)
1	Equally strong	(1,1,1)	(1,1,1)

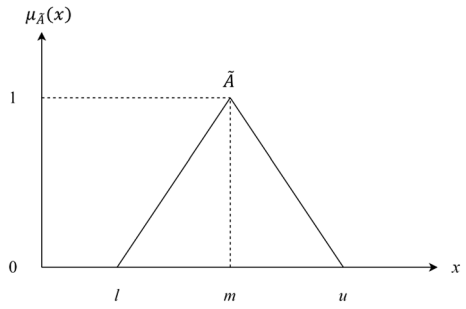


Fig. 2 Membership function of triangular fuzzy number. $\tilde{A}$=fuzzy set, $\mu_{\tilde{A}}(x)$=membership function, l=lower limit of the triangular fuzzy number, m=peak of the triangular fuzzy number, u=upper limit of the triangular fuzzy number

11. Fuzzy weights ($\tilde{w}_i$) are converted into crisp weights (s_i) using Centroid defuzzification method as Eq. 14

$$s_i = \frac{l_i + m_i + u_i}{3}. \tag{14}$$

12. Equation 15 is used to normalize the weights after obtaining the crisp weights

$$T_i = \frac{s_i}{\sum_{i=1}^{m} s_i} \tag{15}$$

T_i is the normalized weight of criterion/sub-criterion i.

13. Next, normalize the crisp weights (s_i) from the alternatives using linear max method whereby Eq. 16 is for the beneficial criteria and Eq. 17 is for the non-beneficial criteria

$$r_{ij} = \frac{a_{ij}}{a_{max}} \tag{16}$$

$$r_{ij} = \frac{a_{min}}{a_{ij}}, \tag{17}$$

a_{ij}, each entry value of comparison matrix where $i=1,2, \ldots, n$ and $j=1,2, \ldots, n$;

a_{max}, maximum value of each column;

a_{min}, minimum value of each column;

r_{ij}, each normalized entry value of the matrix where $i=1,2, \ldots, n$ and $j=1,2, \ldots, n$.

14. Renormalize r_{ij} using the linear sum method to ensure the sum value is 1 whereby Eq. 18 for beneficial criteria and Eq. 19 for non-beneficial criteria

$$r_{ij} = \frac{a_{ij}}{\sum_{i=1}^{j} a_{ij}} \tag{18}$$

$$r_{ij} = \frac{\frac{1}{a_{ij}}}{\sum_{i=1}^{j} \frac{1}{a_{ij}}}. \tag{19}$$

15. Finally, the global preference weight (gw_i) was calculated by multiplying the sub-criteria weight with the respective criteria weight to rank the criteria and sub-criteria and the alternatives were ranked using Eq. 20 based on each alternative's overall performance level in terms of criteria and sub-criteria [67, 69]

$$P_k = \sum_{i=1}^{i=n} gw_i \times w_i, \tag{20}$$

P_k is the overall priority of alternative k under all the criteria/ sub-criteria,

gw_i is global preference weight of criterion/ sub-criterion i,

w_i is weight of the alternative k under the criterion i,

n is number of criteria/sub-criteria.

Study area

The Modified Fuzzy IAHP method is applied to analyze the FWM in Malaysia that addresses the food waste issues in the country and identifies sustainable food waste treatments. Malaysia faces the challenge of food waste, like many other developed and developing nations. The majority of food waste in Malaysia, approximately 80%, is currently disposed of through the landfilling method, which poses significant environmental and health risks [11]. To overcome this challenge, Malaysia is transitioning toward sustainable FWM, exploring various alternatives for a better future. Thus, further research and development are required to address the challenges associated with this issue.

A set of criteria, sub-criteria, and alternatives obtained from the related literature are presented in Tables 1 and 2 [20–29]. To assess the suitability of the criteria, sub-criteria, and alternatives within Malaysian contexts, a validation process was undertaken, wherein these were thoroughly evaluated and confirmed by the related waste management body specializing in FWM in Malaysia. Following the validation process, one sub-criteria (i.e., Noise Impacts) and five alternatives (e.g., Incineration, Hydrothermal Carbonization, and Ethanol Fermentation) were excluded from consideration. The details of considered four criteria, 21 sub-criteria, and their types [beneficial (B) or non-beneficial (NB)] are presented in Table 4. Furthermore, the four alternatives considered include Anaerobic Digestion, Black Soldier Fly, Composting, and Landfilling.

The questionnaire was refined and approved by specialists from a waste management body, following the requirements of the Modified Fuzzy IAHP. Saaty and Özdemir [70] demonstrated that the sample size for decision-makers should ideally range from six to eight individuals, with seven being the closest to the point of least weighted error. In this study, seven specialists from waste management bodies with substantial experience in the FWM sector participated in the survey. The distribution of respondents based on their work experience is shown in Table 5. Despite the small sample size, the feedback received from the specialists is sufficient to evaluate FWM and draw conclusions for this study due to the nature of the method employed. The feedback obtained from the specialists was analyzed using the Modified Fuzzy IAHP method with Excel software.

Results

This section presents the results obtained using the Modified Fuzzy IAHP method, demonstrating its practical application. Sensitivity analysis was conducted to ensure result accuracy, and a comparative study highlights the importance of incorporating normalization in the proposed method. These findings collectively validate the efficacy and relevance of the approach.

Modified fuzzy IAHP application

Before the demonstration, some guidance needs attention from the specialists to ensure that the feedback is suitable for the Modified Fuzzy IAHP methods. First, specialists were required to randomly select one criterion, which may be the most important, and compare it with the other criteria. Assume that a specialist chooses the economic criteria as the first criterion, which may be the most important. Then, the specialist compares it with others (i.e., environmental, social, and technical) one by one to confirm that economic criterion is the most important. There are two scenarios found during the sorting and ranking process:

Scenario 1: Specialist determines that the economic criterion is the most important after comparing it with others. Thus, the economic criterion will be ranked first. Next, the specialist chooses the second criterion from the remaining criteria (i.e., environmental, social, and technical) and repeats the same process until all are ranked.

Scenario 2: The specialist identifies that the environmental criterion is more important than the economic criterion

Table 4 The details of criteria, sub-criteria, and alternatives

Criteria	Sub-criteria	B/NB
Economic (ECO)	Initial investment cost (ECO1)	NB
	Collection and transportation cost (ECO2)	NB
	Operational cost (ECO3)	NB
	Revenue (ECO4)	B
	Employment and job creation (ECO5)	B
Environmental (ENV)	Air & water pollution (ENV1)	NB
	Ecological impact (ENV2)	NB
	Energy consumption (ENV3)	NB
	Greenhouse gas emissions (ENV4)	NB
	Renewable energy (ENV5)	B
Social (SOC)	Law and regulations (SOC1)	NB
	Political support (SOC2)	B
	Public acceptance (SOC3)	B
	Health impacts (SOC4)	NB
	Smell impacts (SOC5)	NB
Technical (TEC)	Capacity (TEC1)	B
	Adaptability to system (TEC2)	B
	Land usage efficiency (TEC3)	B
	Technological maturity (TEC4)	B
	Efficiency (TEC5)	B
	Reliability (TEC6)	B

B: Beneficial sub-criteria; NB: Non-Beneficial sub-criteria.

Table 5 Respondents in relation to working experience

Working experience	Number of respondents
1–5 years	3
6–10 years	2
11–15 years	1
> 15 years	1

after being compared, and the environmental criterion will replace it and be compared with the rest (i.e., social and technical). If the environmental criterion is still the most important after the comparison, it will be ranked first. Next, the specialist chooses the second criterion among the rest (i.e., economic, social, and technical) and repeats the process until all are ranked. If the environmental criterion is substituted by another criterion, then repeat the process until the first-ranked criterion is discovered.

Once all are ranked, the specialist assigns criteria weights based on their importance, with the most important criterion receiving a weight of 10 and the least important receiving a weight of 1. The remaining criteria are assigned using linear interpolation within a range of 2 to 9.

Table 6 represents the comparison matrix between the criteria considered with the objective of this research, which acts as an example to show how to establish the sorting comparison matrix. Based on the example, the scores assigned by this specialist were economic=1, environmental=10, social=7, and technical=8. According to the sorting comparison matrix algorithm, economic was less important than environmental (economic=1<environmental=10), therefore the value of 1/9 was assigned to a_{12} (1/(10−1)); environmental was more important than economic (environmental=10≥economic=1), therefore, the value of 9 was assigned to a_{21} (max(10−1,1)); environmental was equally important as environmental (environmental=10≥environmental=10), therefore the value of 1 was assigned to a_{22} (max(10−10,1)).

The geometric mean was computed using Eq. 2 and normalized with Eq. 3, using the economic criterion as an example and the computations shown as follows:

$$GM_{ECO} = \{1 \times 0.1111 \times 0.1667 \times 0.1429\}^{1/4} = 0.2268 \tag{21}$$

$$w_{Eco} = \frac{0.2268}{(0.2268 + 2.7108 + 1.1892 + 1.3678)} = 0.0413. \tag{22}$$

The C matrix was formed using Eq. 4, and the CV_i and λ_{max} were calculated using Eqs. 5, 6, taking the criteria comparison matrix as an example for the calculation

$$\mathrm{C} = \begin{bmatrix} 1 & 0.1111 & 0.1667 & 0.1429 \\ 9 & 1 & 3 & 2 \\ 6 & 0.3333 & 1 & 1 \\ 7 & 0.5 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} 0.0413 \\ 0.4934 \\ 0.2164 \\ 0.2489 \end{bmatrix} = \begin{bmatrix} 0.1677 \\ 2.0120 \\ 0.8775 \\ 1.0010 \end{bmatrix} \tag{23}$$

$$CV_{Eco} = \frac{0.1677}{0.0413} = 4.0636 \tag{24}$$

$$CV_{Env} = \frac{2.0120}{0.4934} = 4.0782 \tag{25}$$

$$CV_{Soc} = \frac{0.8875}{0.2164} = 4.0542 \tag{26}$$

$$CV_{Tec} = \frac{1.0010}{0.2489} = 4.0211 \tag{27}$$

$$\lambda_{max} = \frac{4.0636 + 4.0782 + 4.0542 + 4.0211}{4} = 4.0543. \tag{28}$$

Equations 7–9 were used to compute the consistency ratio (CR), and the criteria comparison matrix was used as an example

Table 6 Sorting comparison matrix of criteria in relation to the objective

Criteria	Economic	Environmental	Social	Technical	Priority vector
Economic	1.0000	0.1111	0.1667	0.1429	0.0413
Environmental	9.0000	1.0000	3.0000	2.0000	0.4934
Social	6.0000	0.3333	1.0000	1.0000	0.2164
Technical	7.0000	0.5000	1.0000	1.0000	0.2489

$\lambda_{max} = 4.0543$, $CR = 0.0182$

$$CI = \frac{(4.0543 - 4)}{4 - 1} = 0.0181 \tag{29}$$

$$RI = \frac{(1.987 \times (4 - 2))}{4} = 0.9935 \tag{30}$$

$$CR = \frac{0.0181}{0.9935} = 0.0182. \tag{31}$$

Based on Eq. 7, the comparison matrix was acceptable and practicable if *CR* value was less than 0.1. Therefore, the comparison matrices for the criteria and sub-criteria were consistent. Table 7 represents the comparison matrix for criteria in linguistic terms given in Table 3 using Eq. 11. The fuzzy geometric mean for each criterion and sub-criterion, fuzzy weight, crisp weight, and normalized weight were calculated using Eqs. 12–15 as presented in Table 8.

The mentioned calculations were computed using the economic criterion from Table 8 as an example, and presented in the following manner:

$$\tilde{z}^{l}_{\text{Eco}} = (1 \times 0.4325 \times 1.0204 \times 2.0179)^{\frac{1}{4}} = 0.9715 \tag{32}$$

$$\tilde{z}^{m}_{\text{Eco}} = (1 \times 0.6206 \times 1.3810 \times 2.3061)^{\frac{1}{4}} = 1.1857 \tag{33}$$

$$\tilde{z}^{u}_{\text{Eco}} = (1 \times 0.8730 \times 1.8857 \times 2.5952)^{\frac{1}{4}} = 1.4377. \tag{34}$$

The fuzzy weight was calculated by computing the reciprocal fuzzy number, the vector summation of each $\tilde{z}_i$ with (-1) power, placed in increasing order and multiplying $\tilde{z}_i$ with the reverse vector

$$\sum_{j=1}^{j=n} \tilde{z}^{l}_{i} = (0.9715 + 2.0766 + 1.0208 + 0.8031)^{-1} = 0.2053 \tag{35}$$

$$\sum_{j=1}^{j=n} \tilde{z}^{m}_{i} = (1.1857 + 2.4741 + 1.2365 + 0.9015)^{-1} = 0.1725 \tag{36}$$

$$\sum_{j=1}^{j=n} \tilde{z}^{u}_{i} = (1.4377 + 2.8544 + 1.4745 + 1.0517)^{-1} = 0.1467. \tag{37}$$

Vector summation in increasing order=[0.1467 0.1725 0.2053]

$$\tilde{w}^{l}_{\text{Eco}} = 0.9715 \times 0.1467 = 0.1425 \tag{38}$$

$$\tilde{w}^{m}_{\text{Eco}} = 1.1857 \times 0.1725 = 0.2045 \tag{39}$$

$$\tilde{w}^{u}_{\text{Eco}} = 1.4377 \times 0.2053 = 0.2951. \tag{40}$$

The crisp weight and normalized weight were calculated using Eqs. 14, 15 and taking economic criterion as an example for the calculation as follows:

$$s_{\text{Eco}} = \frac{0.1425 + 0.2045 + 0.2951}{3} = 0.2140 \tag{41}$$

$$T_{\text{Eco}} = \frac{0.2140}{1.0380} = 0.2062. \tag{42}$$

The summary of the criteria and sub-criteria that showed the ranking between the criteria and sub-criteria is presented in Table 9.

Table 7 Criteria comparison matrix $\widetilde{\text{A}}$ in linguistic terms

Criteria	ECO			ENV			SOC			TEC		
ECO	1.0000	1.0000	1.0000	0.4325	0.6206	0.8730	1.0204	1.3810	1.8857	2.0179	2.3061	2.5952
ENV	3.0476	3.6429	4.2857	1.0000	1.0000	1.0000	1.8571	2.5714	3.2857	3.2857	4.0000	4.7143
SOC	1.3571	1.9571	2.6071	0.4571	0.5119	0.6190	1.0000	1.0000	1.0000	1.7500	2.3333	2.9286
TEC	1.3968	1.5873	1.8730	0.4226	0.4660	0.5714	0.7048	0.8929	1.1429	1.0000	1.0000	1.0000

Table 8 Criteria output

Criteria	Fuzzy geometric mean			Fuzzy weight			Crisp weight	Normalized weight
ECO	0.9715	1.1857	1.4377	0.1425	0.2045	0.2951	0.2140	0.2062
ENV	2.0766	2.4741	2.8544	0.3046	0.4267	0.5859	0.4391	0.4230
SOC	1.0208	1.2365	1.4745	0.1497	0.2133	0.3026	0.2219	0.2138
TEC	0.8031	0.9015	1.0517	0.1178	0.1555	0.2159	0.1630	0.1571

Regarding the alternatives, the computations both before and after applying fuzzification and defuzzification methods followed a similar procedure as outlined in the preceding calculation steps. Table 10 illustrates the normalized weights of the economic criteria after employing the defuzzification method.

The comparison matrices were subjected to normalization methods once the weights were normalized using Eq. 15. Tables 11 and 12 serve as examples that represent the comparison matrix of alternatives in relation to economic subcriteria using the max normalization method and the sum normalization method, respectively.

The calculation below exemplifies the max normalization method for beneficial criteria concerning the composting method in relation to revenue (refer to Table 11)

$$r_{14} = \frac{0.2746}{\max\left(0.2746, 0.3932, 0.1249, 0.2073\right)} = 0.6984. \quad (43)$$

The calculation below for non-beneficial criteria concerning the composting method in relation to initial investment cost (refer to Table 11)

$$r_{11} = \frac{\min\left(0.2755, 0.3707, 0.2125, 0.1413\right)}{0.2755} = 0.5130. \quad (44)$$

The calculation below exemplifies the sum normalization method for beneficial criteria concerning the composting method in relation to revenue (refer to Table 12)

$$r_{15} = \frac{1}{(1 + 0.6674 + 0.5526 + 0.6062)} = 0.3538. \quad (45)$$

The calculation below for non-beneficial criteria concerning the composting method in relation to initial investment cost (refer to Table 12)

$$r_{12} = \frac{0.8163}{(0.8163 + 0.8287 + 0.5224 + 1)} = 0.2577. \quad (46)$$

In the above demonstrations of the sum normalization method, Eq. 18 was used exclusively for both beneficial and non-beneficial criteria, since they were standardized into beneficial criteria using Eqs. 16, 17. Following the normalization of the values using the max and sum normalization methods, the final ranking for the alternatives was calculated using Eq. 20, as shown in Fig. 3.

The mentioned calculation was demonstrated using composting method (Ranking 2) as an example

$$\begin{aligned} P_{Com} =& \left(gw_{Eco1} \times w_{Eco1}\right) + \left(gw_{Eco2} \times w_{Eco2}\right) \\ &+ \left(gw_{Eco3} \times w_{Eco3}\right) + \left(gw_{Eco4} \times w_{Eco4}\right) + \left(gw_{Eco5} \times w_{Eco5}\right) \\ &+ \left(gw_{Env1} \times w_{Env1}\right) + \left(gw_{Env2} \times w_{Env2}\right) + \left(gw_{Env3} \times w_{Env3}\right) \\ &+ \left(gw_{Env4} \times w_{Env4}\right) + \left(gw_{Env5} \times w_{Env5}\right) + \left(gw_{Soc1} \times w_{Soc1}\right) \\ &+ \left(gw_{Soc2} \times w_{Soc2}\right) + \left(gw_{Soc3} \times w_{Soc3}\right) + \left(gw_{Soc4} \times w_{Soc4}\right) \\ &+ \left(gw_{Soc5} \times w_{Soc5}\right) + \left(gw_{Tec1} \times w_{Tec1}\right) + \left(gw_{Tec2} \times w_{Tec2}\right) \\ &+ \left(gw_{Tec3} \times w_{Tec3}\right) + \left(gw_{Tec4} \times w_{Tec4}\right) + \left(gw_{Tec5} \times w_{Tec5}\right) \\ &+ \left(gw_{Tec6} \times w_{Tec6}\right) \end{aligned} \quad (47)$$

$$\begin{aligned} P_{Com} =& (0.0688 \times 0.2004) + (0.0503 \times 0.2577) \\ &+ (0.0439 \times 0.2372) + (0.0217 \times 0.2746) \\ &+ (0.0216 \times 0.3538) + (0.1167 \times 0.2871) \\ &+ (0.1130 \times 0.3697) + (0.0466 \times 0.3152) \\ &+ (0.0956 \times 0.2190) + (0.0512 \times 0.1592) \\ &+ (0.0659 \times 0.2255) + (0.0471 \times 0.3641) \\ &+ (0.0323 \times 0.2926) + (0.0467 \times 0.3045) \\ &+ (0.0218 \times 0.3294) + (0.0260 \times 0.2153) \\ &+ (0.0215 \times 0.3513) + (0.0330 \times 0.2751) \\ &+ (0.0175 \times 0.3527) + (0.0320 \times 0.2904) \\ &+ (0.0271 \times 0.2791) = 0.2779 \end{aligned} \quad (48)$$

Sensitivity analysis

Sensitivity analysis assists the in-depth study in determining which food waste treatment alternatives are appropriate for the criterion by evaluating the model's criteria. It helps in understanding how criteria and technology relate to one another. On the other hand, sensitivity analysis assists in assessing the dependability of the outcomes produced by each model. The decision-maker evaluates the validity of the prioritized output through comparison. According to Table 9, the environmental criterion is given the highest priority weight among the criteria considered, which can affect the other by changing its weight. Sensitivity analysis was conducted by assigning a range of weights from 0.1 to

Table 9 Final ranking for criteria and sub-criteria

Criteria	RPW for criteria	Sub-criteria	RPW for sub-criteria	Relative ranking	Global preference weight	Global ranking
ECO	0.2062	ECO1	0.3336	1	0.0688	4
		ECO2	0.2439	2	0.0503	7
		ECO3	0.2127	3	0.0439	11
		ECO4	0.1051	4	0.0217	18
		ECO5	0.1047	5	0.0216	19
ENV	0.4230	ENV1	0.2758	1	0.1167	1
		ENV2	0.2671	2	0.1130	2
		ENV3	0.1101	5	0.0466	10
		ENV4	0.2260	3	0.0956	3
		ENV5	0.1209	4	0.0512	6
SOC	0.2138	SOC1	0.3081	1	0.0659	5
		SOC2	0.2206	2	0.0471	8
		SOC3	0.1511	4	0.0323	13
		SOC4	0.2183	3	0.0467	9
		SOC5	0.1019	5	0.0218	17
TEC	0.1571	TEC1	0.1656	4	0.0260	16
		TEC2	0.1368	5	0.0215	20
		TEC3	0.2101	1	0.0330	12
		TEC4	0.1115	6	0.0175	21
		TEC5	0.2035	2	0.0320	14
		TEC6	0.1725	3	0.0271	15

RPW Relative preference weights

Table 10 Comparison matrix of alternatives in relation to economic sub-criteria

Sub-criteria	COM	AD	LF	BSF
ECO1	0.2755	0.3707	0.2125	0.1413
ECO2	0.2292	0.2257	0.3580	0.1871
ECO3	0.2382	0.3883	0.2127	0.1607
ECO4	0.2746	0.3932	0.1249	0.2073
ECO5	0.3538	0.2361	0.1955	0.2145

COM Composting, *AD* Anaerobic Digestion, *LF* Landfilling, *BSF* Black Soldier Fly

Table 11 Comparison matrix of alternatives in relation to economic sub-criteria using Max normalization method

Sub-criteria	COM	AD	LF	BSF
ECO1	0.5130	0.3813	0.6651	1.0000
ECO2	0.8163	0.8287	0.5224	1.0000
ECO3	0.6747	0.4140	0.7556	1.0000
ECO4	0.6984	1.0000	0.3176	0.5271
ECO5	1.0000	0.6674	0.5526	0.6062

Table 12 Comparison matrix of alternatives in relation to economic sub-criteria using Sum normalization method

Sub-criteria	COM	AD	LF	BSF
ECO1	0.2004	0.1490	0.2599	0.3907
ECO2	0.2577	0.2616	0.1649	0.3157
ECO3	0.2372	0.1455	0.2657	0.3516
ECO4	0.2746	0.3932	0.1249	0.2073
ECO5	0.3538	0.2361	0.1955	0.2145

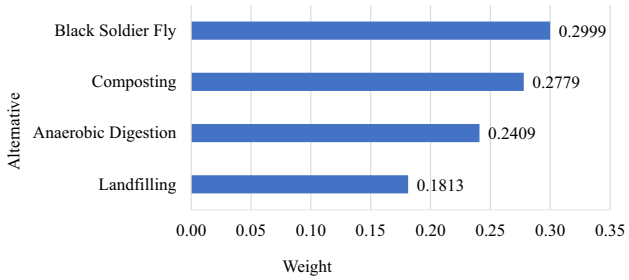


Fig. 3 Ranking for the alternatives

0.9 to the environmental criterion to understand its impacts, as shown in Fig. 4.

The findings presented in Fig. 4 indicate that as the weight assigned to the environmental criterion increased, the weight distributed to the other decreased, with a significant portion allocated to the environment, which resulted in the social being ranked first, followed by economic and technical, respectively. The changes in the weight assigned to the environmental criterion also impacted the global ranking of the sub-criteria, as demonstrated in Table 13. For instance, when the environmental weight was 0.1, ECO1 ranked first, while ENV3 was ranked last. ECO1 remained in the top position until the environmental weight reached 0.3, after which ENV1 took the lead, with the ranking varying until the environmental criterion weight reached 0.9. The other sub-criteria were also affected similarly.

The sensitivity analysis conducted in this study revealed that the ranking of the sub-criteria was affected by changes in the weight of the environmental criterion. Therefore, it is possible to conclude that this requires more attention, because it is crucial to implementing successful FWM. It will help control and minimize the repercussions of the criteria relevant to the use of food waste treatment alternatives if the management team can reduce the environmental effects, which might further improve the environmental performance of the respective treatments.

Comparative study

A comparison was made between the results obtained from the Modified Fuzzy IAHP with and without the

normalization method to demonstrate its significance. The Modified Fuzzy IAHP without normalization uses the same formula as the proposed method but without including Eqs. 16–19 from "Methodology". Figure 5 represents the comparison rankings between Modified Fuzzy IAHP with and without normalization methods.

Figure 5 demonstrates that in the absence of the normalization method, the proposed method indicates that Anaerobic Digestion is the most suitable method for managing food waste, followed by Landfilling, Composting, and Black Soldier Fly. However, the introduction of the normalization method causes a notable shift in this ranking. The Modified Fuzzy IAHP with normalization resulted in identifying the most sustainable alternative. This method provides the normalized weight for each alternative toward all relevant criteria and sub-criteria comprehensively and offers a more holistic view of the alternatives.

In contrast, the Modified Fuzzy IAHP without normalization fails to achieve the same level of accuracy in evaluating the alternatives. This emphasizes the importance of employing normalization to ensure a fair and balanced comparison across different criteria and aspects. Notably, Landfilling should be considered the least desirable option among the alternatives. This stance is supported by its adverse impact on both the environment and public health. The emission of methane and greenhouse gases associated with Landfilling poses significant environmental challenges, making it an option with considerable drawbacks. On the other hand, Composting emerges as a more sustainable alternative compared to Landfilling, as substantiated by Babalola [20, 25], which reinforces the notion that Composting offers better environmental and public health outcomes. Furthermore, Anaerobic Digestion emerges as a promising solution; however, its successful integration in Malaysia encounters several obstacles that undermine its feasibility and sustainability compared with Composting and Black Soldier Fly for sustainable food waste treatment. These challenges include issues such as the substantial investment required for construction and operations, coupled with the absence of localized technological expertise. Despite the limited availability of comprehensive comparative analyses employing the MCDM method to evaluate the Black Soldier Fly against the available alternatives, this alternative is supported by Bernama [71] as the most sustainable food waste treatment in Malaysia. This underscores the value of considering prior research in establishing the sustainability of food waste treatments.

Consequently, the initial ranking that does not incorporate the normalization method is deemed flawed. This ranking fails to consider the complete spectrum of beneficial and non-beneficial criteria toward each alternative weight, leading to an incomplete assessment of the alternatives. The introduction of the normalization method addresses this limitation, leading to a more accurate and robust evaluation of the various waste management methods. In conclusion, the findings emphasize the need to employ appropriate methodologies, such as normalization, in comparative assessments to ensure a fair comparison among alternatives and to enable informed decision-making in FWM practices.

Discussion

Priority for criteria and sub-criteria

Table 9 presents the priority order of criteria and sub-criteria and the global ranking of specific sub-criteria based on their global preference weights. These weights are calculated by multiplying the relative preference weights (RPW) for sub-criteria with their corresponding preference weights for criteria. As shown in Table 9, the environmental criterion (RPW=0.4230) has been identified as the most important criterion, followed by social, economic, and technical criteria.

The findings suggest that food waste specialists in Malaysia prioritize the environmental impact of FWM. It is not surprising considering that most of the food waste generated is landfilled in Malaysia, contributing to the emission of greenhouse gases and methane. It appears that food waste specialists in Malaysia are more willing to take action to minimize environmental impacts than other factors. However, it is worth noting that despite a good understanding of the consequences of food waste, Malaysians have poor environmental consciousness and take little action to reduce it [72]. This highlights the importance of the role played by food waste specialists in raising awareness and promoting sustainable practices in the country.

The food waste specialists in Malaysia appear to be concerned about its social and economic implications. It is essential for achieving sustainable FWM practices that minimize environmental impact and contribute to the well-being of society and the economy, which helps create lasting benefits for all stakeholders and promotes sustainable development in the long run. Interestingly, the food waste specialists expressed the least concern for the technical aspects, which suggests that they are confident in the level of technology available in the country for managing food waste. This is a positive sign, which implies that technological limitations are unlikely to hinder efforts to improve FWM in Malaysia.

The study results reveal that among the sub-criteria, the air and water pollution sub-criterion from the environmental criterion is the most critical sub-criterion (RPW=0.2758). The second and third most important sub-criteria are ecological impact and greenhouse gas emissions, respectively. These results indicate that to select the most suitable food waste treatment alternative, air and water pollution,

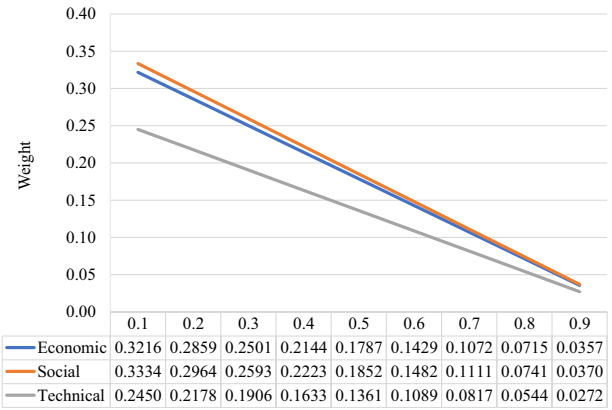


Fig. 4 Criteria weight assigned when environmental criteria increased

Table 13 Ranking for specific sub-criteria by sensitivity analysis when environmental criteria weight changes from 0.1 to 0.9

Sub-Criteria	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
ECO1	1	1	1	4	5	6	6	6	6
ECO2	3	3	6	6	8	8	8	8	8
ECO3	6	6	9	10	11	11	11	11	11
ECO4	13	16	18	18	18	18	18	18	18
ECO5	14	17	19	19	19	19	19	19	19
ENV1	16	7	2	1	1	1	1	1	1
ENV2	18	8	3	2	2	2	2	2	2
ENV3	21	21	14	11	7	5	5	5	5
ENV4	19	10	5	3	3	3	3	3	3
ENV5	20	20	13	9	4	4	4	4	4
SOC1	2	2	4	5	6	7	7	7	7
SOC2	4	4	7	7	9	9	9	9	9
SOC3	8	11	11	13	13	13	13	13	13
SOC4	5	5	8	8	10	10	10	10	10
SOC5	12	15	17	17	17	17	17	17	17
TEC1	11	14	16	16	16	16	16	16	16
TEC2	15	18	20	20	20	20	20	20	20
TEC3	7	9	10	12	12	12	12	12	12
TEC4	17	19	21	21	21	21	21	21	21
TEC5	9	12	12	14	14	14	14	14	14
TEC6	10	13	15	15	15	15	15	15	15

ecological impact, and greenhouse gas emissions are the main concerns of the specialists to improve environmental performance and lessen its effects on the environment in terms of the gases and leachate produced. On the other hand, the technological maturity sub-criterion within the technical criterion was the least important sub-criterion among those considered. This indicates that specialists have confidence in the present technology level in Malaysia to implement specific FWM treatments and are capable of combining with other FWM practices.

Moreover, laws and regulations are the most important sub-criteria among the options considered, suggesting that government rules and constraints play a crucial role in the development and continuation of food waste treatment alternatives. Additionally, the initial investment cost sub-criterion is the most significant factor from the economic criterion, highlighting the significant expenses involved in setting up a food waste treatment plant, including the cost of establishing the facility and opening the disposal site. Furthermore, the land usage efficiency sub-criterion is assigned the highest importance from the technical criterion, indicating that specialists focused on how well the food waste treatment facility could manage limited land resources to treat the waste effectively.

Priority for alternative

Figure 3 presents the overall priority of the alternatives and ranking. It shows that the Black Soldier Fly (RPW=0.2999) performed the best while satisfying the criteria and sub-criteria considered, followed by Composting, Anaerobic Digestion, and Landfilling.

Black soldier fly

Black Soldier Fly treatment has several advantages: (i) the lowest cost in terms of initial investment cost, collection and transportation cost, and operating cost; (ii) the least laws and regulations that limit its development and the health effects on the public; and (iii) the least air and water pollutants and greenhouse gas emissions. In fact, Black Soldier Fly treatment provides a low-cost, long-term source of animal feed that is appropriate for countries with limited treatment technology and insufficient capital [32]. Furthermore, it produced 47 times less greenhouse gas emissions than composting [73]. However, it has several disadvantages: (i) the lowest handling capacity for food waste and technology maturity compared with other treatments, and (ii) the least political support and public acceptance from the relevant agencies in Malaysia. In reality, Raman et al. [74] found that it is difficult to gain the trust to actively replace traditional animal feed with insect meal, because it is a new emerging industry in Malaysia.

In view that the treatment has the lowest potential capacity in handling food waste, these design considerations are suggested for large-scale implementation of the treatment:

i. Site selection

a. Choose a suitable location with minimal environmental impact that should have access to a consistent supply of food waste, preferably from local sources, to reduce transportation costs. The layout should include designated areas for fly breeding, larvae feeding, and larvae collection.

ii. Fly breeding area

a. The control of temperature, humidity and access to sunlight are crucial for breeding structure areas. Alexandra and Dusenbury [75] show that a temperature between 21 °C and 30 °C with a humidity range between 33% and 60% and direct sunlight is recommended for the structure. The blocks like honeycomb cardboard are necessary for egg collection from female flies and should be as close as possible to food sources.

iii. Larvae feeding area

a. Eggs are set to hatch into larvae within 4 days. During this early stage, plastic trays can be utilized to contain both larvae and small amounts of feed/waste. This marks a crucial phase where decomposition occurs, largely driven by larvae digesting food waste. Effective moisture control is vital to prevent odor and feed material decay [76]. Properly designed trays or bays should facilitate moisture drainage, avoiding any pooling liquids. Moreover, the optimal temperature and living conditions play a pivotal role in larval development. A temperature range of 24 °C to 30 °C, coupled with high humidity and a shaded environment, is conducive to fostering optimal larval growth.

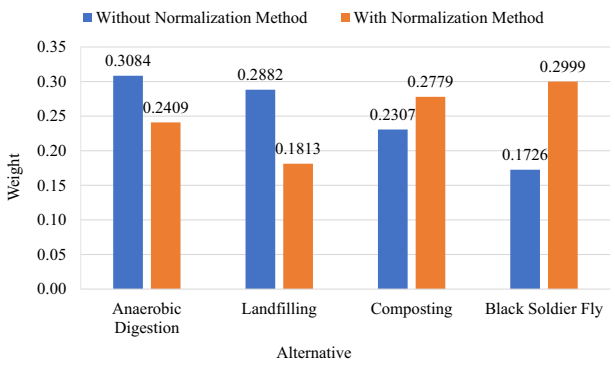


Fig. 5 Comparison among the alternative rankings with and without normalization method

iv. Harvest larvae

a. After a span of 2 weeks, the larvae enter a harvest-ready phase. During this period, the larvae achieve their maximum weight without undergoing the transition into prepupae [76]. This developmental stage marks the maximum of their nutritional value. The harvesting process entails the utilization of either manual or automated screens, facilitating the effective separation of larvae from residual matter. The harvested larvae can be employed as direct feed for animals, while the remaining organic waste can be sun-dried for repurposing as compost.

Apart from that, there are several suggestions for government and private bodies to address its limitations:

i. Launch public awareness campaigns to promote the benefits of the treatment and educate the public on its safety and effectiveness.
ii. Provide incentives and support for businesses to adopt the treatment and create a more favorable environment for the emerging industry of insect meal production.

Composting

Composting treatment stands out with several advantages, including (i) the highest employment and job generation rates, (ii) the least energy consumption and the lowest negative impact on the environment, (iii) the least negative impact on odor, (iv) the highest public acceptance, and public support from relevant agencies, and (v) the highest level of technology maturity and adaptability to the current system. In fact, composting is environmentally friendly, has fewer pollution impacts, and has low technology requirement treatment, which has recently gained popularity in Malaysia [77, 78]. Furthermore, the Public–Private Partnership project is an initiative made by the government to introduce the composting system to the public, which discovers more knowledge in handling food waste [79]. However, it generated the least renewable energy when compared to other treatments.

For these reasons, there are several suggestions for government and private bodies to address its limitations:

i. Encourage composting as a pre-treatment process before other waste-to-energy technologies, such as incineration or gasification, can produce more renewable energy than composting alone.
ii. Develop policies and incentives to promote composting with other renewable energy sources, such as solar or wind power, to maximize the overall contribution to renewable energy generation.

iii. Promoting the utilization of extracellular polymeric substances as bioflocculants offers an environmentally friendly method of managing composting leachate [80].
iv. Design the composting structure for better aeration, maintain proper moisture levels, and regulate temperature, while also incorporating earthworms not only to mitigate greenhouse gas emissions but also to improve the overall quality of the compost for subsequent use [81].

Anaerobic digestion

Anaerobic Digestion is the most efficient in terms of land usage, reliability, and the generation of revenue from the sale of its byproducts, which include energy and fertilizers. According to the United States Environmental Protection Agency [82], Anaerobic Digestion increases revenue and promotes energy independence for farmers while reducing greenhouse gas emissions. However, Anaerobic Digestion is subject to the strictest laws and regulations and has the highest initial investment and operating costs. In Malaysia, several barriers restrict the implementation of Anaerobic Digestion, including high construction and operation costs, lack of local technology for biogas power plants, and a shortage of skilled local staff in managing, operating, and maintaining Anaerobic Digestion plants [83, 84].

For these reasons, there are several suggestions for government and private bodies to address its limitations:

i. Provide financial incentives to encourage private companies to invest in anaerobic digestion technology.
ii. Work with private companies and universities to develop local technology for biogas power plants, reducing the reliance on imported technology and making it more accessible for local businesses.
iii. Provide training programs for operating and maintaining anaerobic digestion plants, increasing the number of qualified workers in the field.
iv. Manage the digestate generated through anaerobic digestion with appropriate procedures, such as dewatering, can lead to its conversion into valuable resources like livestock bedding, soil amendments, and fertilizers.

Landfilling

Landfilling offers the maximum handling capacity for food waste compared to other treatment options. However, it has several drawbacks, including the highest collection and transportation costs due to the need for waste transportation to the landfill site. It also generates the least income and employment opportunities while producing the most greenhouse gas emissions, air and water pollution, and ecological effects. Furthermore, it has significant negative effects on public health and odor and the lowest adaptability to the existing system, land usage efficiency, reliability, and efficiency. Despite having the lowest overall cost, except for collection and transportation costs, landfilling is not a sustainable food waste treatment method, because it generates pollution that harms the environment and public health.

For these reasons, there are several suggestions for government and private bodies to address its limitations:

i. Implement waste reduction and recycling initiatives to reduce waste amount that goes to landfills, thus decreasing the collection and transportation costs.
ii. Develop and enforce stricter regulations to reduce greenhouse gas emissions, air and water pollution, and ecological effects associated with landfilling.
iii. Encourage the implementation of landfilling leachate treatment, such as activated sludge process and membrane separation technology, to handle leachate issues [85].
iv. Encourage the implementation of gas collection systems to control and reduce methane emissions while minimizing the impact on the climate such as reciprocating engines and gas turbines [86].
v. Invest in research and development to improve landfill technology and efficiency, including more efficient waste sorting and disposal methods.
vi. Implement public education campaigns to raise awareness about the negative effects of landfilling on public health and the environment and encourage waste reduction and recycling.

In conclusion, Black Soldier Fly treatment is recommended for waste-management firms as a more sustainable alternative than others. In contrast, landfilling is not considered an ideal waste-management method due to its impacts on the environment, public health, and economy.

Conclusion

This study proposes a novel method called Modified Fuzzy IAHP for evaluating the current food waste treatment alternatives in Malaysia. This method offers a comprehensive analysis of food waste treatment, providing a solution for food waste issues. Previous studies that utilized IAHP faced difficulties in eliminating human judgment and required a more comprehensive approach to provide an accurate

evaluation. The Modified Fuzzy IAHP model addresses these issues by incorporating linear normalization, fuzzification, and defuzzification methods. Despite the small sample size, the feedback obtained from specialists is sufficient to evaluate FWM and draw conclusions for this study due to the method employed. Furthermore, a comparative study has demonstrated the importance of the normalization method's application. Based on the analysis, it is evident that the proposed method with the normalization method can address the influence of beneficial and non-beneficial criteria on the standard scale and provide the most sustainable food waste treatment alternative. Moreover, sensitivity analysis was conducted to assess the Modified Fuzzy IAHP method's performance and stability of the priority ranking for criteria and sub-criteria. The obtained results demonstrate that the study's outputs are consistent and reliable. The outputs suggest that Black Soldier Fly treatment is the most suitable alternative due to its lower environmental impact, cost-effectiveness, and fewer regulatory barriers. On the other hand, Landfilling is not a sustainable alternative and poses significant risks to the environment and public health despite its capacity to manage food waste. These findings offer important insights for policymakers, waste-management practitioners, and other stakeholders in designing and implementing effective FWM strategies that are environmentally sound, economically viable, and socially responsible. There were three limitations found in the study:

i. The weights assigned to the food waste treatment alternatives are based on subjective opinions, which may not accurately reflect the actual performance of each treatment.
ii. The study's findings are limited to Malaysia and may not apply to other countries or regions.
iii. The difficulties in obtaining feedback from the decision-makers are due to the nature of the methodology.

The following recommendations are suggested, as possible extensions of the research covered in this study:

i. Future studies should investigate the actual data of the food waste treatment alternatives for the respective sub-criteria to obtain a more comprehensive understanding of the treatments.
ii. The Modified Fuzzy IAHP method should be extended by incorporating other appropriate tools, such as GIS for location selection, life cycle assessment for analyzing potential environmental consequences, and system dynamics method for understanding variable changes over time according to desired objectives.
iii. The Modified Fuzzy IAHP method should be applied to other MCDM problems to obtain a comprehensive view involving multiple criteria, sub-criteria, and alternatives.
iv. The conceptual framework of this study should apply to other FWM problems in different countries to gain a broader understanding of the treatments.

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Author contributions CYC was responsible for the conceptualization of the research, methodology development, data verification and validation, formal analysis, investigation, and data curation, as well as writing the original draft and final editing. SA-R, AMY, and EEA-J provided valuable contributions through writing, reviewing, editing, and supervision. All authors have read and approved the final manuscript.

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Data availability The supporting data for the findings of this study can be obtained from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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