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Challenges and solutions for food waste-based biogas in Malaysia

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ABSTRACT

This study aims to identify and rank policy options to inform development of an enabling environment for food waste-based biogas production for energy generation in Malaysia, taking into account stakeholder perspectives. The analysis focuses on stakeholders from Malaysia whose responses are analysed using the analytic hierarchy process. Literature searches identified sixteen challenges and twenty-eight solutions, which were analysed under environmental, institutional and legal, economic and resourcing, technical and social and cultural categories. Findings rank the economic and resourcing category highest (28.6 %), followed by the institutional and legal category (26.1 %), social and cultural (21.6 %), technical (12.9 %) and then environmental categories (10.9 %). Identifying a good balance between the scale of plant, food waste distribution and collection with a weight of 46.4 % dominates the solutions, followed by constant socialisation with the community to emphasise the importance of shifting from landfilling or incineration to biogas (44.6 %). Implement nationwide operational management standards, optimise operational parameters of the biogas digester, and target major waste producers (i.e., catering enterprises) and enforce waste segregation at source were solutions positioned respectively in third, fourth and fifth position with weights of 22.2 %, 19.9 % and 17.4 %. Substituting fossil fuels with renewable resources such as biogas where possible will reduce climate change alongside other environmentally damaging impacts, and supports progress towards climate action (SDG 13). The output of this study can inform policy development for food waste-based biogas production for energy generation in both Malaysia and globally.

1. Introduction

Rapid industrialisation and population increases have led to increased global energy consumption [1]. The primary source of energy in most countries comes from fossil fuels which contribute to the greenhouse gas emissions that cause global warming [2]. Reducing emissions while meeting growing energy demands requires increased use of renewable energy [3]. Simultaneously, Asia is experiencing a rapid increase in food waste generation which can be linked to processes of globalisation, urbanisation, industrialisation, and population growth [4]. Segregation and collection of food waste are not well practised in developing Asian countries and food waste is mostly sent to landfill (90 % of food waste treatment) [5]. The issue of mounting food waste presents a serious threat, and its management has not yet received the required attention, investment or urgent emphasis within policy [6].

Several studies have performed policy analysis on food waste-based biogas production for energy generation. Clercq et al. [7] used multi criteria decision analysis to evaluate food waste to biogas projects in China at pilot scale and their policy implications. The study included environmental, economic, and technical aspects, ranked from best to worst using a multi criteria decision analysis framework. Ranking using the analytic hierarchy process (AHP) including economic, market, technical and awareness considerations, was used to identify non-technical and technical barriers impeding the adoption of biogas technology in rural households in India [2]. Yang et al. [8] conducted Strength, Weakness, Opportunity, and Threat analysis for restaurant food waste for biogas production in China, while Kumar et al. [9] identified barriers concerning waste management in India. In Australia, a feasibility study was conducted that considered environmental, economic, and technological aspects of using food waste as a source of sustainable energy, but it did not consider stakeholders' perspectives [10]. Bong et al. [11] reviewed policies on solid waste management and renewable energy policies on biogas development in Malaysia but did not consider technical barriers to increasing biogas yield or challenges associated with continuous production.

Most prior studies do not involve stakeholders, unlike the analysis carried out in this paper. Although Yadav et al. [2]'s study in India is an exception, they did not consider environmental, institutional and legal barriers; nor did they perform a ranking of the solutions given.

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Nomenclature

Abbreviations

AHP	Analytic hierarchy process
AD	Anaerobic digestion
CR	Consistency ratio
SDG	Sustainable Development Goals

Symbols

λ_{max}	Largest eigenvalue
n	Number of attributes

Environmental aspects are at the core of sustainability [12], while institutional and legal aspects shape how policies and laws are regulated and enforced, so this would seem an important omission. Understanding stakeholders' perspectives is important because they best reflect the situation in a particular location, and have opinions based on real-world experiences in negotiating the current policy context. The literature is lacking investigations that include stakeholders' views in relation to what is needed to create a comprehensive enabling environment for food waste-based biogas production for energy generation. An enabling environment covers the attitudes, policies and practices and is a form of encouragement for people to take successful actions [13] and is inclusive of factors contributing to effective institutions and governance within an individual country and a particular sector. Proper policy, supported by an enabling environment, plays a crucial role in effective waste management and is important if Asian countries are to continue to progress towards achieving the Sustainable Development Goals.

This study aims to identify and rank challenges and policy options for food waste-based biogas production for energy generation in Malaysia, taking into account stakeholder perspectives. Possible solutions to tackle the identified challenges were also listed and ranked. The analysis provided extends approaches in existing studies and considered five different categories: environmental, institutional and legal, economic and resourcing, technical as well as social and cultural aspects.

Malaysia was used as the case study focus. Malaysia is a developing country facing rapid population growth and urbanisation. The country has a population of 34.3 million [14] which is, projected to reach 37.4 million by 2030 [11]. Two major issues for Malaysia's development are energy security and solid waste management [11], particularly food waste management. Food waste contributes to 44.5 % of the total solid waste composition in Malaysia [15]. Through the Paris Agreement, the country has pledged to reduce its greenhouse gas emissions by 45 % by 2030 [16]. In 2015, Malaysia's primary energy production mix showed the highest percentage contribution from natural gas (50.9 %), then coal (25.6 %), hydro (15.9 %), diesel (4.4 %), biomass (2.4 %), solar (0.5 %). Biogas contributed the least (0.1 %) [17].

This study extends work that recognises the need for energy generation from diverse source. For example, a total of 17.24 Megawatts of energy generated from biogas comes only from palm oil mills that treat palm oil mill effluent [18]. This demonstrates the need to explore different alternatives for energy generation in Malaysia. The food waste generated in the country has also increased from 16,688 tonnes/day (in 2016) [19] to 17,000 tonnes/day (in 2022) [20], in line with population growth. The findings could inform the development of an enabling environment to foster growth in this area, while helping to advance towards the Sustainable Development Goals (SDGs). In advancing understanding in this way, the research will support progress towards affordable and clean energy (SDG 7) alongside transitions toward net zero (SDG 13, climate action).

2. Methods

A conventional literature search was undertaken to identify challenges and solutions related to food waste-based biogas production for energy generation. Findings were manually refined to only include articles that had this focus, leaving twenty journal articles, from which sixteen challenges and twenty-eight solutions were extracted. There were then compiled in a survey conducted with stakeholders from Malaysia. During the survey, participants were asked to rank the challenges and solutions faced globally and in Asian countries. Survey responses were then analysed using AHP. AHP is a ranking and prioritisation tool introduced by Saaty [21] and was used in this study to identify possible ways to support an enabling environment for food waste-based biogas production for energy generation. The following section sets out our sampling process, with the subsequent section explaining the AHP process.

2.1. Sampling and participant selection

There are numerous analytical, hybrid, heuristic, simulation and mathematical programming models that can be used to inform decision making. For example, mathematical modelling can be used to deal with wide range of complex issues and has high flexibility. However, the linearisation between two variables may be unrealistic [22]. Simulation methods require high computational power [23] while heuristic models can resolve complex, non-linear data and cover a large scale but are unable to solve problems in the missing coordinate system [22]. Hybrid methods offer an integrative and holistic framework for sustainability assessment but lack proper tools and software [24]. Multi criteria decision analysis is the most common method used under the analytical model approach, and is commonly undertaken with small, specific groups of decision makers to reduce the inconsistencies that may arise in a larger group of participants [25]. After evaluating numerous options, the AHP method was employed as an analytical approach that can support decision making [26]. AHP is commonly used to quantify and demonstrate experts' views [27].

A survey was conducted with fourteen respondents, following the AHP process. About sixty potential respondents in Malaysia were approached, but after repeated follow ups, only fourteen responded and were therefore taken as sample. The authors' institution's ethics committee gave approval before the data collection. Data was collected from respondents based in Malaysia. Respondents were initially identified through online web searches followed by snowball sampling [28] which played crucial role in identifying the subsequent respondents. Each respondent was asked to recommend different or similar potential respondents. Respondents were selected based on their knowledge and expertise in relation to food waste conversion to value added products and were people who felt they also had sufficient knowledge on anaerobic digestion (AD) to provide meaningful responses. An AD technology provider focused on using agricultural and livestock waste as resource for biogas production in Malaysia was also included in the sample.

The methodology of this study is not without challenges. Using food waste for biogas production in Malaysia is still relatively rare, which indirectly influences the number of respondents who took part in the survey, while our snowball sampling (where a respondent recommends a further respondent) may be influenced by the closed network of the person who is recommending them. To address this issue, internet searches were used to identify the relevance of the newly recommended contacts and to identify further respondents, providing multiple starting points to improve the reliability of the approach. The final sample size of respondents achieved, though on the small side, is considered acceptable because there is no evidence on the exact number of respondents required to justify the output of the AHP result. AHP can be used when there is one or more respondents according to the literature [29]. The survey was conducted online using Zoom.

2.2. Analytic hierarchy process (AHP)

The AHP method has four major steps which are as follows [21]: a) the problem is defined and then a hierarchy is formed with the goal at the highest level; b) a questionnaire or pairwise comparison survey is then undertaken for respondents to reflect their perspectives using a 9 point scale; c) a pairwise comparison matrix is constructed in relation to the challenges and solutions identified based on the categories involved, according to the information derived from the second step. To attain agreement in the pairwise judgement, the geometric mean method is used [30] and d) the degree of randomness in the judgements used to develop the matrix is calculated [31] by taking into consideration the Consistency Ratio (CR). The CR is crucial in measuring the consistency and reliability of the judgement [21] which is calculated through the division of consistency index and random index. The judgement matrix is considered to have met the consistency requirements if the CR < 0.1 [32]. Equation (1) shows the calculation for the consistency index. In this equation, λ_{max} is denoted as the largest eigenvalue and n is the number of attributes.

$$CI = (\lambda_{max} - n) / (n - 1) \quad (1)$$

AHP captures only a snapshot of participants' perspectives. Consequently, their views may change over time so can only be considered to represent their perspective at the time of data collection.

3. Results

3.1. Challenges and solutions for food waste-based biogas production for energy generation

Detailed descriptions of each challenge and solution identified for each category and the weightings calculated using AHP are further explained in Subsection 3.2.

3.2. Environmental challenges and solutions

Table 1 contains the environmental challenges related to food waste-based biogas production for energy generation where 'challenges in identifying sustainable food waste resource allocation' (58.0 %) is viewed as more demanding than the 'challenges in reducing environmental impacts associated with transportation of food waste to the biogas facility' (42.0 %). Respondents mentioned that there are various alternatives in converting food waste into value added products. The best alternatives based on the feedback from the respondents seem to emphasise economic factors such as profitability. Also, there is a still lack of proven best routes that could help to reduce the environmental burdens.

'Identifying a good balance between the scale of plant, food waste distribution and collection' (46.4 %) was ranked highest under the 'environmental' solution category in the AHP, followed by the statement that 'anaerobic digestion is the most sustainable way of managing food waste' (35.7 %) and 'waste collection distance to the biogas facility should be less than 10 km' (17.9 %). AD is one of the best ways to treat food waste while attempting a balanced distance between the plant, food waste distribution and collection so this could help in tackling environmental challenges. The CR for the challenges and solutions is 0.000 and 0.016, respectively.

3.3. Institutional and legal challenges and solutions

Table 2 lists the 'institutional and legal' challenges in which 'lack of proper waste segregation and collection' (50.9 %) was found to be the highest priority. Respondents felt this could be best dealt with by 'imposing fines for food waste value chain stakeholders who fail to meet government objectives' (20.0 %) which was ranked the highest under 'institutional and legal' solutions. This solution is part of the Solid Waste and Public Cleansing Management Act (Act 672) [33] in Malaysia. This initiative runs in several states (Kedah, Perlis, Pahang, Malacca, Negeri Sembilan and Johor) including two Federal states (Putrajaya and Kuala Lumpur). However, according to one of the respondents, the mandate is not implemented in these locations.

The second highest ranked 'institutional and legal' solution was to 'reduce the threshold level for the amount of organic waste that waste producers can generate without converting to resources' (12.1 %) followed by setting a 'clear division of labour' (6.2 %) which could further enhance the waste segregation and collection process. The second highest ranked 'institutional and legal' challenge was 'lack of proper standards for waste management' (27.0 %) followed by 'improper waste disposal method' (22.2 %). 'Implementing nationwide operational management standards' (22.2 %) could offset the lack of proper waste

Table 1
Environmental challenges and solutions for food waste-based biogas production for energy generation.

Category	Sub-category	Priority weight (%)	Category	Sub-category	Priority weight (%)
Environmental (challenges)	Challenges in identifying sustainable food waste resource allocation	58.0	Environmental (solutions)	Anaerobic digestion is the most sustainable way of managing food waste	35.7
	Challenges in reducing environmental impacts associated with transportation of food waste to biogas facility	42.0		Identifying a good balance between scale of plant, food waste distribution and collection	46.4
				Waste collection distance to the biogas facility should be less than 10 km	17.9

Table 2
Institutional and legal challenges and solutions for food waste-based biogas production for energy generation.

Category	Sub-category	Priority weight (%)	Category	Sub-category	Priority weight (%)
Institutional and legal (challenges)	Lack of proper waste segregation and collection	50.9	Institutional and legal (solutions)	Impose fines for food waste value chain stakeholders who fail to meet government objectives	20.0
	Lack of proper standards for waste management	27.0		Reduce the threshold level for the amount of organic waste that waste producers can generate without converting to resources	12.1
	Improper waste disposal method	22.2		Clear division of labour	6.2
				Implement nationwide operational management standards	22.2
				Improve collection and transportation capacity to food waste treatment facility	22.0
				Support/increase the construction of food waste treatment facilities	17.5

Table 3
Economic and resourcing challenges and solutions for food waste-based biogas production for energy generation.

Category	Sub-category	Priority weight (%)	Category	Sub-category	Priority weight (%)
Economic and resourcing (challenges)	Poor efficiency in waste segregation and collection	30.4	Economic and resourcing (solutions)	Sign agreement on waste collection contracts	8.8
	Challenges in getting a constant supply of feedstock for biogas digester	26.0		Supply free and different coloured liners for food waste	3.6
	Challenges in dealing with high operational and maintenance costs of the biogas plant	17.5		Provide residual bin stickers and food caddy stickers	2.7
	Challenges in dealing with high installation costs of biogas digester	13.5		Target major waste producers (i.e., catering enterprises) and enforce waste segregation at source	17.4
	Unstable revenue	12.6		Installation of biogas digester (i.e., anaerobic sequencing batch reactor) with lower operational costs	14.0
				Install locally manufactured parts for the biogas plant	8.5
				Provide easy loans and tax exemptions	16.6
				Provide subsidy based on operational performance rather than subsidising installation costs	14.3
				Provide subsidy to the amount of biogas consumed instead of the amount of biogas produced	14.1

management standards issue nationwide. To tackle the issue of 'improper waste disposal method', 'improving collection and transportation capacity to food waste treatment facility' (22.0 %) and 'support/increase the construction of food waste treatment facilities' (17.5 %) were the recommended solutions. The CR for the challenges and solutions is 0.067 and 0.013, respectively.

3.4. Economic and resourcing challenges

'Economic and resourcing' challenges listed in Table 3 show that 'poor efficiency in waste segregation and collection' (30.4 %) was ranked highest, while 'signing agreement on waste collection contracts' (8.8 %) was ranked the highest under 'economic and resourcing' solutions for this challenge. Having a contract signed could not only guarantee a continuous source of food waste supply but also ensure orderly segregated waste is coming from the supplier. 'Supply free and different coloured liners for food waste' (3.6 %) and 'provide residual bin stickers and food caddy stickers' (2.7 %) were the two other recommended solutions to enhance the efficiency of waste segregation and collection. These solutions were reported to be effective in one of the guidelines introduced for food waste segregation and collection in the United Kingdom (the Waste and Resources Action Programme) [34]. While the United Kingdom example is a pilot plant study, it resulted in positive developments for food waste segregation and collection at household level. The second highest ranked 'economic and resourcing' challenge was 'challenges in getting a constant supply of feedstock for the biogas digester' (26.0 %). This could be addressed by 'targeting major waste producers (i.e., catering enterprises) and enforcing waste segregation at source' (17.4.%). Catering enterprises commonly deal with a high volume of food waste so could make a useful contribution to the organisation by converting food waste to energy.

The statement 'challenges in dealing with high operational and maintenance costs of the biogas plant' (17.5 %) was ranked the third highest 'economic and resourcing' challenge in the AHP. This could be best dealt through 'installation of biogas digesters (i.e., anaerobic sequencing batch reactor) with lower operational costs' (14.0 %) and by 'installing locally manufactured parts for the biogas plant' (8.5 %). 'Challenges in dealing with high installation costs of biogas digester' (13.5 %) was ranked the fourth highest 'economic and resourcing' challenge followed by 'unstable revenue' (12.6 %). There are two solutions for the fourth challenge which are: 'provide easy loans and tax exemptions' (16.6 %) and 'provide subsidy based on operational performance rather than subsidising installation costs' (14.3 %). The solution for the lowest ranked 'economic and resourcing' challenge was to 'provide a subsidy for the amount of biogas consumed instead of the amount of biogas produced' (14.1 %). The CR for the challenges and solutions is 0.045 and 0.019, respectively.

3.5. Technical challenges and solutions

'Challenges in technological maturity' (27.1 %) was found to be the highest priority within the 'technical' challenges (Table 4). This challenge was felt by respondents to be best addressed through 'increased collaboration between government, universities, and private

Table 4
Technical challenges and solutions for food waste-based biogas production for energy generation.

Category	Sub-category	Priority weight (%)	Category	Sub-category	Priority weight (%)
Technical (challenges)	Challenges in technological maturity	27.1	Technical (solutions)	Increased collaboration between government, universities, and private corporation	16.6
	Challenges in increasing biogas yield	26.6		Joint ventures with foreign countries to improve technical skills	10.3
	Challenges in transmitting the energy generated from biogas to the national grid	24.4		Optimise operational parameters of the biogas digester	19.9
	Lack of trained manpower	21.9		Co-digestion with other types of waste and pre-treatment of food waste	19.8
				Use multi stages biogas digester	6.4
				Decentralised anaerobic digestion system is better at transmitting energy generated to the grid	10.8
				Capacity building and training	16.1

Table 5
Social and cultural challenges and solutions for food waste-based biogas production for energy generation.

Category	Sub-category	Priority weight (%)	Category	Sub-category	Priority weight (%)
Social and cultural (challenges)	Poor public awareness towards waste segregation	77.0	Social and cultural (solutions)	Conduct regular engagement with the community (door-to-door service)	39.2
	Challenges in encouraging conversion of food waste to biogas among community	23.0		Constant socialisation with the community to emphasise the importance of shifting from landfilling/incineration to biogas	44.6
				Conduct zero waste campaign	16.3

corporations' (16.6 %) and 'joint ventures with foreign countries to improve technical skills' (10.3 %). The second highest ranked 'technical' challenge was 'challenges in increasing biogas yield' (26.6 %). There are multiple solutions for this challenge including: 'optimising operational parameters of the biogas digester' (19.9 %), 'co-digestion with other types of waste and pre-treatment of food waste' (19.8 %) and 'use multi-stage biogas digesters' (6.4 %). The third most highly prioritised challenge was 'challenges in transmitting the energy generated from biogas to the national grid' (24.4 %). It is recommended that 'decentralised anaerobic digestion systems are better at transmitting energy generated to the grid' (10.8 %). 'Lack of trained manpower' (21.9 %) was ranked the lowest under the 'technical' challenges. The solution to this challenge is to have constructive 'capacity building and training' (16.1 %). Capacity building and training is already in place in most of the organisations involved in this research. However, the content of the training conducted could be varied according to the employees' technical knowledge in operating the digester. The CR for the challenges and solutions is 0.017 and 0.016, respectively.

3.6. Social and cultural challenges and solutions

In Table 5, the 'social and cultural' challenges have been detailed, where 'poor public awareness towards waste segregation' (77.0 %) is viewed as more challenging than the 'challenges in encouraging conversion of food waste to biogas among the community' (23.0 %). 'Conducting regular engagement with the community (door-to-door service)' (39.2 %) is one of the recommended ways to better educate the public to segregate their food waste in a proper manner. The solution for the lowest ranked 'social and cultural' challenge is to have 'constant socialisation within the community to emphasise the importance of shifting from landfilling/incineration to biogas' (44.6 %) and to 'conduct zero waste campaigns' (16.3 %).

Conducting zero waste campaigns was ranked the lowest as numerous movements and programs have already been conducted, yet waste management continues to face barriers, with little to no food waste segregation being carried out at the household level in Malaysia. This was also found to be the case by Nordin and Adman [35] who conducted a study on the awareness of solid waste segregation at the household level in Banting, Selangor, in Malaysia. Of 20 respondents in the survey, none practiced waste segregation at home [35]. The CR for the challenges and solutions is 0.000 and 0.061, respectively.

4. Discussion and conclusion

In terms of policy recommendations, the most important category to consider is 'economic and resourcing' (28.6 %). 'Target major waste producers (i.e., catering enterprises) and enforce waste segregation at source' which comes under the 'economic and resourcing' solutions were ranked the highest in the AHP. It is clearly understood by respondents that it is crucial to have a consistent supply of food waste to ensure that production runs smoothly and that there is a need for community support to properly segregate waste at the initial stage to ensure continuous production of biogas for energy generation. This can be further strengthened by 'signing agreements on waste collection contracts'. Signing contracts with major waste producers such as catering enterprises could help guarantee the constant source of feed supply for the AD. Lessons could be learnt here from regulations in France that encourage catering food to be recycled (in AD facilities), redirecting the food waste from landfills [36].'Provide easy loans and tax exemptions' which comes under the 'economic and resourcing' solutions was ranked the second highest in the AHP, 0.8 % lower than the highest ranked solution. The Malaysian Investment Development Authority allocates an investment tax allowance, introduced in 2014, for consumers investing in green technology assets/equipment. Investment tax allowance is an allowance of 100 % for qualified capital expenses such as machinery, factory, plants and equipment which have been approved for projects [37]. The issue with investment tax allowance is getting the approval from both the GreenTech and Malaysian Investment Development Authority, which makes it less attractive to investors as the procedure is not straightforward [38]. This slows down the process of encouraging implementation of green technology in Malaysia.

'Installing locally manufactured parts for the biogas plant' is one of the important 'economic and resourcing' solutions emphasised by respondents. It is encouraged to use locally manufactured parts for the biogas plant to ensure that the plant can operate continuously without being shut down for a month or two for the biogas digester parts to be imported whenever there is a breakdown. Another respondent mentioned that the efficiency of the technology would be the same regardless of the countries from which the technologies are imported. The efficiency of the digester mainly depends on the design criteria and not the types of technology used. Furthermore, 'installation of biogas digesters (i.e., anaerobic sequencing batch reactors) with lower operational costs' could eventually reduce the capital and operational costs when the plant is also constructed with locally manufactured parts for the digester. The lowest ranked 'economic and resourcing' solution was to 'provide residual bin stickers and food caddy stickers'. This solution was suggested based on one of the initiatives in the United Kingdom that seeks to improve the household level food waste segregation and collection [34]. In Malaysia, there are caddy stickers for recycling purposes but not specifically for food waste segregation. In addition, one of the respondents mentioned there are no food waste bins allocated and no waste segregation is taking place even though it is mandated to do so in several states in Malaysia. Thus, usage of residual bin stickers and food caddy stickers is a less attractive option for the respondents as it is quite an uncommon practice in Malaysia. However, the combined solutions of 'providing residual bin stickers and food caddy stickers' and 'supplying free and different coloured liners for food waste' which have been practised at pilot scale in the United Kingdom has resulted in a positive outcome and encourages the community to segregate their food waste [34].

The second highest ranked category was 'institutional and legal' (26.1 %). The highest ranked 'institutional and legal' solution was to 'implement nationwide operational management standards'. There is an existing regulation, the Solid Waste and Public Cleansing Management Act (Act 672) adopted in 2007, focusing on Solid Waste Management in Malaysia, but as one of the respondents mentioned, that regulation is quite outdated and needs to be revised. For instance, penalties, such as fines for failed waste management, are only implemented in some states

(Kedah, Perlis, Pahang, Malacca, Negeri Sembilan and Johor) including two Federal states (Putrajaya and Kuala Lumpur). This clearly demonstrates the need to standardise the regulation nationwide for better waste management. Combining two different solutions 'imposing fines for food waste value chain stakeholders who fail to meet government objectives' and 'implementing nationwide operational management standards' under the 'institutional and legal' category could better enhance the efficiency of food waste separation and collection in Malaysia.

The second highest ranked 'institutional and legal' solution was to 'improve collection and transportation capacity to the food waste treatment facility' which sat 0.2 % lower than the highest ranked solution. Waste collection facilities should be further improved in Malaysia as the majority of food waste is still being directed to landfill. There are not any large-scale food waste treatment facilities available within the country, with existing facilities only operating at lab or pilot scale. Generating energy using food waste at scale has not been properly considered in Malaysia, with the majority of installations being small and used by the community to provide gas for cooking. Apart from this, some respondents mentioned that they are composting food waste. The lowest ranked solution under this category was 'clear division of labour'. This insight was taken from China [39], a country which has an established food waste-based biogas production for energy generation system in the country. However, this option seems to be less attractive for the respondents as the food waste-based biogas production for energy generation is still at lab or pilot scale in Malaysia.

The 'social and cultural' category was ranked third in the AHP (21.6 %). 'Constant socialisation with the community to emphasise the importance of shifting from landfilling/incineration to biogas' which was ranked the highest solution under this category could better help in encouraging the implementation of food waste-based biogas production for energy generation in Malaysia. According to one of the respondents, community awareness of food waste segregation is very low. The community needs to be repeatedly educated and informed about the importance of converting food waste to biogas which can then be used to generate energy. The focus of the government is mainly on the energy sector rather than food waste issues, despite that an estimated 10 % of the country's greenhouse gas emissions are coming from food waste [38]. It remains expensive to install biogas facilities to treat food waste, with estimates suggesting it costs USD 4080 to setup an AD system near residential areas in Malaysia [40].

According to one respondent, Malaysia is not facing any land scarcity issue, thus, it is generally seen as acceptable if food waste is being directed to landfill. A study by Woon et al. [41] reported that more than 80 % of food waste is being directed to open landfill in Malaysia. This suggests that the residents of Malaysia have low awareness of the importance of segregating food waste due to lack of governmental support. The lowest ranked solution under this category was to 'conduct zero waste campaigns'. This possible solution was taken from Australia where Lee et al. [42] report on the importance of complementing waste conversion to energy with other waste reduction efforts to fully achieve zero waste goals [42]. However, one of the respondents mentioned that the concept of zero waste has long been around and may not be efficient in Malaysia.

The 'technical' category (12.9 %) was ranked the fourth highest in the AHP and 'optimise operational parameters of the biogas digester' was the highest ranked 'technical' solution. It is crucial to look into the operational settings of the biogas digesters to improve efficiency in biogas production. 'Co-digestion with other types of waste and pre-treatment of food waste' was the second highest ranked 'technical' solution; 0.1 % lower than the highest ranked solution. One of the respondents shared their experience working on pilot scale food waste-based biogas production for cooking. The biogas production did not last long with only food waste used as the input resource, so now they co-digest the food waste with cow dung to combine the various microbes, which helps to sustain biogas production for longer. A study by Makhura et al. [43] reported that the optimum mixing ratio of cow dung: food waste is 1:2 with 25,595.7 Nml biogas yield compared to other various mixing ratios of 2:1 (18,756.6 Nml), 3:1 (13,839.1 Nml), 1:3 (13,940.8 Nml) and 1:1 (14,042.5 Nml). Nml represents normal millilitre. This work indicates that co-digestion of food waste and cow dung helps to increase biogas yields, suggesting, co-digestion of other materials with food waste will be essential to increase the reliability and efficiency of biogas production if it is to advance in the Malaysian context.

The lowest ranked 'technical' solution was to 'use multi-stage biogas digesters'. Technically, multi-stage biogas digesters help to separate the acidogenesis and methanogenesis process taking place in AD. The first stage covers the acidic conditions while the second stage sustains the alkalinity condition making it suitable for the reactions to take place in a way that helps to increase the biogas yield [44]. Most of the survey respondents have only used a single stage biogas digester. While one of them did agree that multi-stage biogas digesters result in a better biogas yield, it may not be economically viable. A study by Hagos et al. [44] reported that two stage digesters can have complicated operating systems and can be costly, despite their ability to overcome issues related to volatile fatty acid inhibition. They could also aid in studying the microbial variations and populations in the system. Concerns about cost are, however, further supported by a report mentioning that multi-stage AD systems have a higher operational and maintenance cost compared to single stage systems [45].

'Increased collaboration between government, universities, and private corporations' seems to be a more attractive solution than 'joint ventures with foreign countries to improve technical skills' in terms of 'technical' solutions. One of the respondents suggested that they had better improvements in technical aspects by collaborating with one of the local universities in Malaysia compared to collaborating with neighbouring countries such as Thailand. This is because the nature of food waste differs when it involves two different countries, so different conditions are needed to digest the different compositions of the food waste. Thus, collaborating with government, universities and private corporations in-country could better help in improving the technical skills to operate the biogas digesters.

Among the five main categories, the lowest ranked category was the 'environmental' (10.9 %) category. The highest ranked solution under the 'environmental' category identified through the AHP was 'identifying a good balance between scale of plant, food waste distribution and collection'. The lowest ranked solution was 'waste collection distance to the biogas facility should be less than 10 km'. This solution was taken from a study on life cycle assessment by Tian et al. [46] comparing centralised and decentralised AD, which suggested shortening the food waste collection distance from 30 km to 10 km. This solution seems to be less applicable in Malaysia however, as most of the current applications are still at lab or pilot scale. Nevertheless, the distance should still be considered should upscaling take place.

Findings from this study can be used to enhance the enabling environment for the implementation of food waste-based biogas production for energy generation in Malaysia, offering the potential to address important SDGs such as affordable and clean energy (SDG 7) and Malaysia's transition towards net zero (SDG 13, climate action). Most previous studies did not consider stakeholders' perspectives and even those that did, did not consider all the important categories of challenges and solutions. This study consequently fills an important research gap by including all the important categories from the literature to best reflect the scenario in Malaysia. While challenges and solutions in this study considered multiple categories, further research could look into different bundles or combinations of solutions.

Future studies can consider incorporating a political category related to the governmental support and commitment in addition to the categories covered in this study. Additionally, the number of participating respondents could be increased, including more relevant stakeholders, particularly policymakers. The challenges and solutions suggested were based on inputs from literature from other countries. Thus, it is important that the suggested solutions are relevant to the Malaysian context. As such, they may require further critical scrutiny prior to being taken up. The output of this study which takes into consideration global and Asian countries' experiences will nevertheless be useful for future studies.

CRediT authorship contribution statement

Siva Raman Sharvini: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Lindsay C. Stringer:** Supervision, Conceptualization, Methodology, Writing – review & editing, Project administration.

Declaration of Competing 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.

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Data availability

No data was used for the research described in the article.

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