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RESEARCH ARTICLE

CHALLENGES AND SOLUTIONS FOR FOOD WASTE-BASED BIOGAS PRODUCTION FOR ENERGY GENERATION IN MALAYSIA: A REVIEW

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ABSTRACT

Food waste can be anaerobically digested for biogas generation resulting in more sustainable waste management than using landfill, as well as providing clean energy. This paper reviews the challenges faced globally in using food waste-based biogas production for energy generation. It identifies feasible solutions for each challenge based on real-world case study scenarios and pilot plant studies, exploring their implications for Malaysia. Identified challenges and solutions are analysed under five headings: environmental (challenges: 2, solutions: 3), institutional and legal (challenges: 3; solutions: 6), economic and resourcing (challenges: 5; solutions: 9), technical (challenges: 4; solutions: 7) and social and cultural (challenges: 2; solutions: 3) categories. Key findings include that: (1) waste collection distance to the facility should be <10 km to reduce environmental impacts (as implemented in Singapore); (2) it is vital to set a proper division of labour and nationwide standards, as well as increasing food waste treatment facilities (as implemented in China); (3) installation of low cost digesters and reduced operational costs can help to tackle economic challenges (as shown in examples from China and South Korea), while initiatives to obtain a constant supply of food waste can help address resourcing challenges; (4) co-digestion and pre-treatment of food waste are crucial to avoid technical errors (as seen in China and South Korea) and (5) regular engagement with the community can help create awareness on food waste segregation (as demonstrated in the United Kingdom). Tackling the challenges within and across categories could help policymakers to improve existing waste management and renewable energy policies in Malaysia. Solutions given for each challenge emerging from this study offer important inputs to food waste-based biogas production both in Malaysia and globally.

KEYWORDS

Organic waste, policies, renewable energy, green energy, sustainability

1. INTRODUCTION

Globalisation, urbanisation, industrialisation, and population growth are some of the drivers of enormous increases in food waste generation, particularly in Asian countries (Joshi and Visvanathan, 2019). In Malaysia, 98% of total municipal solid waste (MSW) consists of household waste, industrial and commercial wastes which have the potential to generate landfill gaseous emissions such as methane, carbon dioxide and greenhouse gases (Yip and Chua, 2008). Every nation can tackle the global energy and environmental crisis by taking appropriate actions to venture into renewable energy to different extents. Biogas is one of the potential renewable alternatives to fossil fuels, being relatively odourless, inflammable, combustible and colourless (Igoni et al., 2007; 2008). Biogas can be generated through anaerobic digestion, a biological treatment process. Currently, anaerobic digestion is the most environmentally friendly means of converting waste into value-added products such as bioenergy (Li et al., 2019). Biogas production is one of the most effective ways to manage food waste sustainably particularly in developing countries. A study by Joshi and Visvanathan reviewed and evaluated different ways of managing food waste sustainably in Asia by applying the Strength, Weakness, Opportunity, and Threat (SWOT) matrix as a framework for analysis (Joshi and Visvanathan, 2019). The study analysed five available food waste treatment options in Asian countries: landfilling, incineration, use as animal feed, aerobic digestion (composting) and anaerobic digestion to determine the most sustainable way of managing food waste. Anaerobic digestion was concluded to be the best available treatment option compared to other available methods.

Many researchers have studied biogas generation (in general) in various countries, with a few studies making comparisons to understand the prominent aspects applicable for the growth of biogas industries. A study compared biogas policies in China and Europe with a view to improving the biogas industry in China (Xue et al., 2020). Several policy suggestions and measures were considered. Findings reported that the development of biogas industries in European countries are much further ahead, and consequently, successfully implemented case studies can provide useful insights that can be adapted by other (developed and developing) countries (Xue et al., 2020). A study reviewed the barriers in implementing biogas industries derived from various feedstocks in developing and developed countries, categorising the barriers into six groups (environmental, socio-cultural, institutional, market, economic and technical) and concluded that sharing experiences between countries can be beneficial, offering important lessons (Nevzorova and Kutcherov et al., 2019).

In the context of food waste-based biogas generation, identified and ranked barriers (economic, market, awareness and technical) to

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household biogas plants in India (Yadav et al., 2022). Economic barriers were concluded to have had the highest impact on household biogas plants, with high installation creating the most substantive challenge. Another study focused on restaurant food waste for biogas production in China using SWOT analysis (Yang et al., 2019). Their findings could be useful for policymakers, helping them to make better decisions by prioritising the strengths, while robust actions can be taken to encounter weaknesses, now they have been identified. Harnessing opportunities from further exploitation of restaurant food waste and cooperation of relevant governmental departments combating the threats emerged as crucial for enhancing food waste-based biogas production in China. Research by reviewed policies relevant to food waste-based biogas production from all over the world (Clercq et al., 2017a). However, they did not look across environmental, social and economic perspectives.

This study addresses this knowledge gap by providing a more comprehensive analysis considering all pillars of sustainability. It aims to review food waste-based biogas production for energy generation globally, extending the review and identifying the challenges and feasible solutions encountered in different locations and their applicability in Malaysia (Nevzorova and Kutcherov et al., 2019). It identifies the challenges and solutions, placing them under the different categories examined in previous reviews (environmental, institutional and legal, economic and resourcing, technical and social and cultural) and explores their relevance to the current situation in Malaysia. In incorporating this wide range of categories, we provide a more comprehensive understanding of food waste-based biogas production for energy generation through anaerobic digestion and how the various challenges and solutions in the literature might apply to the Malaysia case. The review's findings provide important ways forward for policymakers to further improve their existing policies on solid waste management and renewable energy.

Malaysia offers a useful case study as it faces challenges experienced by many developing world nations, including rapid population growth and urbanisation (Bong et al., 2017). The population is projected to reach 37.4 million by year 2030. While the population rate increases, the food waste generated in the country has also increased from 16,688 tonne·day-1 (in 2016) to 17,000 tonne·day-1 (in 2022) (Sharif, 2023; Hani, 2022). The recycling rate of food waste is only 5% with the rest being disposed in landfills along with other MSW (Lim et al., 2016). Currently, food waste segregation is still unusual in Malaysia with certain households in rural areas practicing open burning, illegal dumping, and burial. Available food waste disposal and treatment facilities are open landfill (>80%), sanitary landfill (15%), use of food waste as livestock feed (at a small scale, <5%), and for composting purposes (at a small scale, <5%) (Woon et al., 2021).

In Malaysia, conversion of food waste to organic fertiliser and animal feed are practiced modestly. However, not all types of food waste are suitable for animal feeding according to Act 698, the Feed Act in Malaysia (LoM, 2009). Improper utilisation of food waste as animal feed can result in the spread of infectious diseases such as mad cow disease, highly pathogenic avian influenza, swine fever and foot-and-mouth disease (Shurson, 2020). Another option is the production of organic fertiliser via an aerated windrow composting which is also being practiced in Malaysia. However, the market demand influences the production of fertiliser derived from food waste (Woon et al., 2021).

Conversion of food waste to renewable energy can be an alternative option in Malaysia in line with the nation's pledge to achieve carbon neutral by 2050 (Hamid, 2017). Also, the Government strives to increase the renewable energy mix to 20% by 2025 and reduce its 40% carbon emissions intensity of Gross Domestic Product by 2030 compared to the level in 2005 under the National Renewable Energy Policy (Woon et al., 2021). The 11th Malaysia Plan (2016-2020) emphasised green growth for sustainability and resilience as one of the main six strategic thrusts, with sustainable consumption and production practices in energy being highlighted (EPU, 2021). Under this plan, waste being sent to landfill can act as resources that can be reused for power generation, recycling and recovery, and other waste-to-wealth efforts. The plan seeks transformation to a resource and energy saving community by managing waste holistically, encouraging low carbon mobility, improving demand side management, increasing share of renewable energy in energy mix, and developing green markets. According to Ibrahim, conversion of food waste to biogas via anaerobic digestion could be a strategic option to improve nation's climate change governance considering the latest enabling policy for carbon trading in Malaysia (Ibrahim, 2021). Bursa Malaysia introduced a voluntary basis carbon market exchange in December 2022 to allow industries to offset their emissions, buy carbon credits and achieve internal climate missions (Joshi and Cortez, 2023). As such, there are many opportunities and driving forces that also make this a timely analysis for Malaysia.

The system boundary of food waste-based biogas production for energy generation covers all the main stages of the process, beginning with the waste segregation and collection, while biogas generation mainly focuses on the feed input, biogas generation including the type and operational parameters of biogas digesters and energy (biogas) distribution. Creating an enabling environment is crucial to ensure Malaysia achieves its fullest potential in managing food waste sustainably, while increasing the contribution of renewable energy in the energy mix by learning lessons from other countries in Asia and globally.

2. Methods

A conventional literature search was conducted using reliable scientific databases: Web of Science, Science Direct and Scopus. The terms "biogas" AND "food waste" were used to search the literature. A guideline on food waste segregation and collection was identified through a Google search using the keyword "food waste collection". Web of Science, Science Direct and Scopus were used to retrieve the first 300 search results, that were published between 2012 and 2023 plus reports that were published in 2012, 2014, 2015 and 2016 (one per year). Also, one policy document published in 2010 was included. Similar articles that were found in either one of the databases were considered as one finding. We decided to use the first 300 search results based on the methods in a study which used systematic review to analyse the first 200 search results (Thorn et al., 2020).

Findings were further manually refined to include only relevant publications, resulting in 20 journal articles (Web of Science:8/Science Direct:10/Scopus:2). Articles were considered relevant and were included if they focused on food waste-based biogas production for energy generation (including lab/pilot/industrial scales) or offered solutions to challenges related to food waste-based biogas production. To minimise inclusion of outdated technical challenges given the field is rapidly evolving, our search was limited to those papers published after 2012 except for the policy document.

In the pursuit of managing food waste sustainably, the challenges and solutions identified were summarised in view of determining appropriate and feasible policy actions and measures for food waste-based biogas facilities in Malaysia. For this we used five main categories focusing on the food waste to biogas distribution pipeline: i) environmental, ii) institutional and legal, iii) economic and resourcing, iv) technical and v) social and cultural which emerged in an inductive way from the data.

3. Review Of Food Waste-based Biogas Production For Energy Generation Challenges And Solutions Identified In Previous Research

Our literature search found that China and the Global region have the largest number of publications in this research field [n=6, 30% contribution each] followed by Hong Kong and Asian region [n=2, 10% contribution each] and the remaining countries (Singapore, South Korea, India, Sweden, and Australia) with n=1, 5% contribution each to the sampled articles.

3.1 Environmental category

Food waste disposal to landfill can contribute up to 11-13% of greenhouse gas emissions globally, suggesting most of the countries that signed the Kyoto Protocol and subsequent agreements would want to reduce emissions from the current 'business as usual' practice (Awasthi et al., 2019; Ragnauth et al., 2015). Greenhouse gases from landfill consist of mainly carbon dioxide and methane. Methane emission from biodegradable waste decomposition via open dumping can accrue in explosions and fire and become a major source of global warming, while open waste dumps have detrimental effects on the public health and environment (Sridevi et al., 2012; Sharholy et al., 2008).

It has been estimated that 125 m^3 of landfill gases are emitted from a tonne of landfilled food waste (Adhikari et al., 2006). Limiting the global average temperature rise to below 2 °C or below 1.5 °C through the Paris Agreement provides a driver for some countries to reduce their greenhouse gas emissions by banning the landfilling of food waste (Joshi and Visvanathan, 2019). This has resulted in a major shift from landfilling to other options such as incineration, fermentation, anaerobic digestion, composting (aerobic digestion) and animal feeding in Asian countries. Anaerobic digestion helps to meet climate change target under Paris Agreement which has the potential to reduce 10-13% of total world's greenhouse gas emission (EBA, 2023). Anaerobic digestion is also assessed to hold potential for greater economic and environmental benefits compared to aerobic digestion (Joshi and Visvanathan, 2019). Conversion of food waste to energy is gaining attention by being an economically attractive option and environmentally beneficial in line with increasing concerns on environmental quality, waste disposal and high economic value associated with energy supply and overall can help support progress towards Sustainable Development Goal (SDG) 7 on clean energy, and help to combat climate change (SDG 13) (Ferdes et al., 2022; Obaideen, 2022; Welfle and Roder, 2022).

Aerobic digestion requires a relatively longer period for decomposition, has a poor fertile compost, mostly turns out to be an incomplete treatment method due to technical barriers, and demands large space requirements (Körner and Visvanathan, 2013; Storey et al., 2013). High concentrations of non-organic pollutants and heavy metals from foreign materials derived from poor food waste segregation may adversely affect soil structure and disrupt plant growth (Cerda et al., 2018). These challenges have led to transition of large-scale composting plants to smaller scale decentralised ones. For example, about 70 aerobic composting plants across major cities in China had been built by 2003. Most of them were either discontinued or closed by 2012 because of a multitude of reasons such as poor sales and poor composting quality (Dou, 2015).

Incineration enables an 80-85% reduction of waste sent to landfill (Khoo et al., 2010). However, food waste incineration has been the least favoured option in most of the previous studies due to the non-combustible components and high moisture content of the waste (Pham et al., 2015). High moisture content in food waste will result in low combustibility rate in the incinerator. Thus, mixing with other waste will eventually reduce the moisture content in the food waste and increase its combustibility rate. Singapore is one of the few countries globally that has widely implemented waste-to-energy or incineration methods that include food waste, largely driven by limited land area for landfill (Khoo et al., 2010). Utilisation of food waste for energy generation rather than sending it to landfill could greatly reduce issues such as contamination of groundwater and greenhouse gas emissions (Soomro et al., 2021). The findings clearly show that food waste treated anaerobically has a better chance of achieving sustainability through biogas generation for energy production when compared to landfill and thus as well as SDG7, it could contribute towards the development of sustainable cities (SDG 11), fostering new partnership (SDG 17) in the process (Piadeh et al., 2024).

Looking further into anaerobic digestion, a life cycle assessment by compared centralised and decentralised anaerobic digester (Tian et al., 2021). Small-scale centralised anaerobic digester can be monitored more easily than a large-scale centralised anaerobic digester, as existence of a blind spot in a large system could result in failure of small organic matter detection. The study also suggested that shortening the distance of food waste collection from 30 km to 10 km could reduce the environmental impacts. This nevertheless requires a balance to be reached between the collection distance, food waste distribution in the surrounding area and the plant.

3.2 Institutional and legal category

Inefficient waste segregation and collection is one of the most critical issues and the most basic thing that needs to be addressed before waste can be converted into value-added products. This challenge could be addressed by setting a threshold level to the permitted daily waste produced by consumers. Another option is to impose penalties such as fines on food waste value chain stakeholders who fail to meet legally binding objectives. Both methods have been a success in France in ensuring waste is directed to the right stream, with the approach also widely implemented in the European Union (Ingremeau, 2014). Apart from proper waste segregation, it is crucial to have a clear workforce to ensure the separated waste can be collected and delivered efficiently to treatment facilities. This is recognized in one of China's policy documents: "On strengthening food kitchen waste oil remediation and waste management opinions" (NDRC, 2010). It provides a regulation with a detailed breakdown on food waste management including collection and transportation of waste, actions on illegal acts and establishes a waste management profile. Also, the regulation gives a clearer picture on the handling and treatment methods of kitchen waste, sets out clear division of tasks across multiple departments, and recognizes the importance of education on proper waste disposal methods as well as the need for monitoring and strengthening of waste management processes.

Another policy document in China focused "On the strengthening of comprehensive solid waste disposal and pollution control work" detailing objectives to enhance the collection and transportation capacity of food waste as well as supporting construction of more food waste treatment facilities (NDRC, 2010). The above-mentioned objectives are the basis for the development of food waste-based biogas production for energy generation in any country so offer important lessons. Robust government support is the backbone of successful policy implementation and regulatory enforcement, as well as for the development of renewable energy industries. It is crucial to outline a proper policy framework to manage any system effectively. This also suggests the converse is problematic: non-standardised nationwide regulations could also result in waste management failure. Lack of proper food waste management standards can be best addressed through implementation of nationwide operational management standards as suggested for food waste treatment (Clercq et al., 2017a). This is now developing in China.

3.3 Economic and resourcing category

In terms of economic and resourcing, proper waste segregation plays an important role in sustaining the food waste-based biogas production for energy generation process. Guidelines to improve this at household level can be taken from The Water and Resources Action Programme (WRAP), UK guidelines (WRAP, 2016). A pilot plant study conducted in the UK by this group eventually provided extended support to local authorities and resulted in a positive improvement to food waste segregation and collection. They note that each step taken to ensure effective food waste segregation and collection from the source is imperative for effective food waste management and disposal. Guidelines in WRAP suggested actions such as providing a free supply of bin liners by the local authority, a leaflet and package of residual bin stickers without any charges to waste producers (WRAP, 2016). This reduces the cost barriers for many households to segregate and has a better coordination setup. In that way, residents are happier to recycle their waste. Simultaneously, providing different colored liners could make the differentiation process much easier and more effective in waste segregation, separation and collection from MSW, as found in Hong Kong by (Woon and Lo, 2016; Lo and Woon, 2016). However, it required the liners to be paid for in advance by the users. This raises important questions about the distribution of costs and benefits across different stakeholders and requires further assessment.

Apart from waste segregation and collection, a constant supply of feedstock is important in enabling continuous biogas production. Waste collection contracts with big restaurants could help to sustain feedstock supply to the digesters (Clercq et al., 2017b). A study by reported that 86% of the people surveyed from catering enterprises showed their willingness to improve their food waste management in Beijing, China (Juan et al., 2014). Targeting major waste producers like catering enterprises could thus help to address supply challenges faced by biogas digesters. An alternative approach has been used in Germany, where from 2015 onwards, the government set regulations for waste segregation with all bio-waste separation to begin from the source (household). This further increases the efficiency waste segregation but requires enforcement (LLIE, 2015).

A study suggested that anaerobic sequencing batch reactors are more efficient in removing volatile solids compared to continuous stirred tank reactors (Wang et al., 2022). Also, the anaerobic sequencing batch reactor enables a longer hydraulic retention time (amount of time needed for the reaction to take place in the digester) which leads to higher biogas yields compared to the continuous stirred tank reactor. The anaerobic sequencing batch reactor further results in lower operational costs, a lower volume of biogas residue and a better conversion efficiency of organic matter compared to the continuous stirred tank reactor. The anaerobic sequencing batch reactor also has a lower installation cost. Both investment costs and operational costs are equally important in determining the feasibility of a biogas production system. One of the ways to handle this challenge is by utilising locally manufactured parts for the biogas plant, as suggested by in South Korea (Kim et al., 2012). In this way, the installation cost burden could be further reduced, while delivering other local economic benefits. Lower capital investment is required for anaerobic digesters operating in wet conditions (≤10% dry matter) while less operating energy is used for anaerobic digesters operating in dry conditions (15-20% dry matter). These savings are made as less water needs to be heated compared to wet conditions and the system tends to produce more gas per unit of feedstock in dry conditions (Caruso et al., 2019).

Barriers related to household waste management in rural area in India for biogas generation were identified and ranked using the analytical hierarchy process (Yadav et al., 2022). The high installation cost of the biogas digester was ranked the highest among all the barriers identified. However, the gap between total installation costs and government subsidies can be managed through allocation of manageable loans (with low interest) for poorer rural households. Such loans could be coupled with wider publicity about the benefits of biogas, and strict implementation of environmental protection policies to encourage rural households to switch from traditional solid biofuel to biogas. In South Korea, tax exemption provides one of the major economic supports for biogas development for the development of food waste-based biogas production (Clercq et al., 2017a).

The Chinese government often encourage provision of subsidies for biogas facility installation. However, the Beijing Actual project proposed performance-based subsidies instead of investment-based subsidies, as there were many operational issues encountered after installation. The government subsidised more than half of the installation costs, but this led to failures in assuring continuous operation, affecting both agricultural biogas plants in general and food waste-based biogas production in China (Clercq et al., 2017b).

The most important revenue stream from anaerobic digestion of biogas generation is the profit obtained through the sale of electricity to the grid- a key element influencing investor decision-making. Commonly, a tariff is provided for the full output of electricity supplied for a certain period of time. In contrast, a report from Finland suggested a subsidy should be provided based on the amount of biogas consumed instead of the amount of biogas produced, to avoid biogas being categorised as a low-cost product (Rasi et al., 2012). In Beijing, China, the biogas project depends on profit obtained through waste treatment fees in which this way of allocating revenue results in zero value for the product (biogas) obtained. To achieve stability in revenue income, providing rewards for the amount of biogas consumed has a greater chance of sustaining biogas production.

3.4 Technical category

Anaerobic methods can degrade complex organic material without oxygen, whereas aerobic digestion requires oxygen for complete degradation. Biogas generated through methane formation resulting from efficient anaerobic digestion serves as fuel for energy generation purposes. Anaerobic digestion consists of 4 main stages: i) hydrolysis, ii) acidogenesis, iii) acetogenesis and iv) methanogenesis (Ahmad et al., 2003; Perez et al., 2001; Poh and Chong, 2014; Appels et al., 2008; Davis and Cornwell, 2013). The first stage, hydrolysis, is where complex waste components (lipids, polysaccharides, proteins, and cellulose) are hydrolysed into their simplest forms, such as fatty acids and amino acids, with the aid of heterogenous groups of facultative and anaerobic bacteria.

The output from the hydrolysis process is further split during acidogenesis (Perman et al., 2022). Products such as hydrogen sulphide, carbon dioxide, ammonia and other traces amounts of gases along with acidogenic bacteria are formed by volatile fatty acids, while hydrogen, carbon dioxide and acetic acid are digested products by acetogens from higher organic acids and alcohols in the acetogenesis stage (Capson-Tojo et al., 2016). Methanogenesis is the final stage and focuses on methane production via two groups of methanogenic bacteria: (1) acetate is further split into carbon dioxide and methane and (2) hydrogen is used as an electron donor and carbon dioxide as an acceptor (Appels et al., 2008). The overall process flow is depicted in Figure 1.

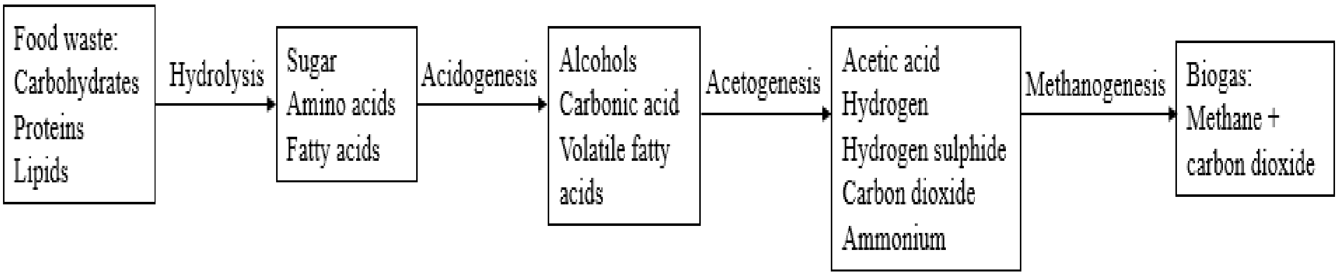

Figure 1: Stages of anaerobic digestion of food waste (Ferdes et al., 2022)

There are myriad treatment technologies available to convert food waste to biogas. Anaerobic digestion of food waste must nevertheless be executed carefully as quick degradation could lead to a subsequent drop in pH level and accumulation of volatile fatty acids (Perman et al., 2022). High levels of protein could lead to inhibition of the fermented product such as ammonia which could be toxic to the microbial community, particularly the methanogenic community (Capson-Tojo et al., 2016; Deepanraj et al., 2014). In phase-separated processes, proteins are not being degraded in the acidogenic stage (Xu et al., 2018). A suggestion was made by some researchers that protein degradation could better take place in a phase-separation reactor rather than a single reactor (Hagos et al., 2017). Such an approach would enable protein degradation in the methanogenic chamber while acidification of carbohydrates could take place in the other chamber.

A study by showed that implementation of serial systems showed a higher methane yield of >5% compared to a single reactor, with most of the methane being produced in the first stage reactor (Perman et al., 2022). Protein degradation is also much better in serial systems compared to a single reactor, producing a 20% higher protein concentration and increase in ammonium concentration with every reactor step. The ultimate limitation of using a single reactor is the formation of acidic conditions in the single reactor due to the presence of acidogenic bacteria. This may hinder the activity of methanogenic bacterial groups, disrupting the conditions required for the optimum methane yield.

Optimum conditions suitable for all types of bacteria are lacking in the single stage reactor which is one of the main limitations (Deepanraj et al., 2014; Xu et al., 2018). The single stage reactor would accrue lower investment and operational costs, lower retention time, lower organic loading rate and possess a pH range of 6-7 compared to the two-stage process, however, it would yield a lower methane rate (Xu et al., 2018). The multi-stage process (or dual process) involves separate anaerobic reactors. The first reactor mainly involves hydrolysis, acidogenesis and acetogenesis while the second reactor only involves methanogenesis. A two-stage process is preferable to accommodate the acidic conditions required for acidogenesis, with low hydraulic retention time in the first reactor, whereas methanogenic bacteria perform better in an optimum pH of 6-8 with high organic loading rate in the second reactor. A study by reported that the two-stage process enhances the efficiency of volatile solid removal, pathogen manageability, improves process stability, has a higher organic loading rate and increased methane production, leading to increased biogas yield (Hagos et al., 2017). However, the complexity involved in the operational, capital and maintenance costs present drawbacks to the two-stage process. Optimising the parameters of a biogas digester is key to enhancing the methane yield (Ferdes et al., 2022).

Biological additives could enhance the effectiveness of anaerobic digestion through bioaugmentation and co-digestion, showing that co-digestion of green biomass (different parts of plants and crop residues) along with food waste could support the anaerobic digestion process (Zhang et al., 2014). Co-digestion processes involve the digestion of a co-substrate, helping to increase the yield of the anaerobic digestion process, providing nutrients for microbes and positive interactions generated in the digestion medium (Dalvi et al., 2023). Food waste pre-treatment which could enhance biodegradability could also improve biogas production by accelerating the rate-limiting stage in the anaerobic digestion process (hydrolysis). Additionally, pre-treatment reduces the retention time needed for anaerobic digestion processing. Few available pre-treatment methods (chemical, biological, thermal, and mechanical) can be used for food waste.

Most pre-treatment enables solubilisation of food waste, whereas chemical and mechanical pre-treatments result in reduced size particles. Chemical, thermal, and mechanical pre-treatments can enhance the solubility of organic components. However, pre-treatments applied to food waste must be done carefully as food waste contains easily degradable organic materials. Ultrasound-aid pre-treatments could result in lower retention times and higher methane production volumes in co-digestion of sludge, food waste and cattle manure (Quiroga et al., 2014). It is nevertheless advisable not to apply ultrasound pre-treatments to food waste but only to sludge and manure due to its lower biodegradability. Microwave-assisted pre-treatment on methane yields from food waste accrued a lower efficiency compared to sewage sludge. Pre-treatment to food waste should be executed with proper planning, in accordance with the properties of the food waste (Mirmohamadsadeghi et al., 2019).

Apart from optimising biogas digesters, it is crucial to share knowledge and expertise with other countries with longer experience in handling food waste-based biogas production for energy generation. A study by emphasised the importance of technical assistance to assure the sustainability of biogas plants and to ensure continuous biogas production (Pandyaswargo et al., 2019). The Chinese government has been collaborating with private corporations and universities for better development of biogas projects nationwide (Clercq et al., 2017a). Knowledge sharing and technological advancement through collaboration with other countries and parties would eventually improve the credibility of the biogas projects. At the same time, inadequate labour and human capacity will not result in a successful operation of the biogas digesters, even where technical knowledge exchange is taking place (Yadav et al., 2022). Other than that, decentralised anaerobic digestion has a better mean of supplying biogas to the end-consumer compared to centralised anaerobic digestion system due to storage and transportation challenges (Joshi and Visvanathan, 2019).

3.5 Social and cultural category

Zero waste practices have been widely implemented through various movements and programs focusing on additional organic streams and increased recycling rates by converting landfill waste to value added products (Woroniecka, 2020). Zero waste can nevertheless only become reality if waste management authorities go beyond waste minimisation to avoid failure in achieving zero waste. For example, in Australia, zero waste practices failed because of the low recycling rate. To fully achieve zero waste, facilitation of waste utilisation via energy recovery, rationing and complementing existing waste reduction strategies are important (Lee et al., 2020).

Besides zero waste practices, regular face-to-face engagement has resulted in improved community recycling rates. Community engagement to increase awareness on shifting waste from sea disposal and incineration to biogas was shown to be a key sustainability factor for the waste management authority in Oki, India. Similarly, a pilot plant study conducted at household level in the UK was a success and received positive feedback from the local authorities involved because of the regular direct engagement with the public. Ongoing community engagement gives a better picture of how the waste management system works in a particular area and enables co-design to fit local needs and concerns (WRAP, 2016).

3.6 Summary and way forward for Malaysia

Our study focused on food waste-based biogas production for energy generation and identified challenges and solutions emerging globally and in Asian countries considering environmental (Table 1), institutional and legal (Table 2), economic and resourcing [Tables 3(i-ii)], technical (Table 4) and social and cultural (Table 5) categories. Food waste is the key input for biogas production for energy generation using anaerobic digestion. In terms of environmental aspects, it is imperative to identify the most sustainable way of managing food waste despite the environmental benefits of treating food waste through anaerobic digestion. Even though anaerobic digestion can be a more environmentally friendly option to treat food waste compared to other approaches, other environmental impacts associated with this process need to be taken into consideration.

However, a life cycle assessment study with four food waste disposal methods (open landfill, sanitary landfill, anaerobic digestion and aerated windrow composting) conducted by in Malaysia resulted in anaerobic digestion being the most environmentally friendly route (Woon et al., 2021). With 80% food waste disposal rate, the conversion of fossil fuels to biogas derived from anaerobic digestion used for energy generation could contribute to 1.1% of total energy consumption in Malaysia and a 0.4% reduction of total carbon emissions (Woon et al., 2021). As such, Malaysia should consider employing anaerobic digestion instead of open landfilling in food waste management in order to achieve a sustainable circular economy (Woon et al., 2021).

Institutional support is undeniably crucial to implement food waste-based biogas production for energy generation in any country. Supporting measures such as increasing the number of treatment facilities and capacity could greatly enhance the efforts to achieve sustainable food waste management through anaerobic digestion. At the same time, stringent laws, and associated enforcement, such as imposing hefty fines for failed waste management, could ease the process of treating food waste for biogas production for energy generation. Household waste segregation for recycling purpose has been made mandatory under the Solid Waste Management (SWM) 2007 by the Malaysian government. An adaptation period was given for residents to get used to the system, after which a fine of up to RM 1,000 was imposed upon those who fail to segregate their solid waste, according to Act 672 (PoM, 2007).

This initiative runs in several states (Kedah, Perlis, Pahang, Malacca, Negeri Sembilan and Johor) including two Federal states (Putrajaya and Kuala Lumpur) and offers potential for anaerobic digestion efforts to begin in these areas. However, it is crucial to implement nationwide operational management standards to improve the overall efficacy of waste management in Malaysia (Bong et al., 2017). Also, involvement of multiple agencies in waste collection makes coordination difficult and expensive in Malaysia (Bong et al., 2017). Thus, it is evident that clear division of labour plays important role in enhancing waste collection.

Food waste is the major source of feedstock for the biogas production. Biogas generation from food-waste heavy MSW fed directly to anaerobic digester is something yet to be developed in Malaysia. The methane yield highly depends on the operational parameters of the digester and feedstock, while the general public in Malaysia have a very low level of social awareness on the importance of waste segregation (Bong et al., 2017). This suggests awareness-raising efforts are needed. At the same time, a consistent supply of food waste could be achieved through engagement with large waste producers and involvement of authorities to underwrite the costs involved in food waste segregation and collection. Clear descriptions as to the requirements of food waste separation could give a better understanding, along with enforcement of waste segregation at source, making the latter process more efficient.

Waste segregation at source is clearly lacking in Malaysia. A study demonstrating the performance of waste to energy production using MSW in Universiti Putra Malaysia (UPM) was conducted (Zulkifli et al., 2019). A survey involving cafeterias and restaurants in UPM showed that many are not practicing waste segregation at source as there is no regulation asking them to do so and due to a lack of awareness. Nevertheless, the restaurants have shown their interest and willingness to take part in proper waste segregation at source if they are instructed to do so (Zulkifli et al., 2019). Besides the need for a constant food waste supply, the high costs involved in the installing and operating biogas digesters could make the approach less attractive for investors. This is evident in Malaysia as economic feasibility and technological maturity are some of the key challenges faced for biogas generation (Ahmad and Tahar, 2014).

Subsidy allocations, tax exemptions and encouraging the use of locally manufactured technology could greatly reduce cost burdens and make it a more feasible option. Currently, financial incentive in the form of tax relief is being provided by the Malaysian government to encourage the utilisation of renewable energy and to ease its development (Bong et al., 2017). However, it was reported by that complexity in the tax application process in Malaysia has slowed down the transition to green technologies as show in Figure 2 (Sharvini et al., 2022). While government and other authorities are the major actors in supporting economic feasibility in food waste-based biogas production for energy generation, there is a need for them to work more closely with the private sector and investors.

Table 1: Summary of the challenges and solutions for environmental category

Category	Challenges	Solutions	Country/Region	Reference
Environmental	Challenges in identifying sustainable food waste resource allocation	Anaerobic digestion is the most sustainable way of managing food waste	Asia	Joshi and Visvanathan, 2019
	Challenges in reducing environmental impacts associated with transportation of food waste to biogas facility	Waste collection distance to the biogas facility should be less than 10 km	Singapore	Tian et al., 2021
		Identifying a good balance between the scale of plant, food waste distribution an collection		

Table 2: Summary of the challenges and solutions for institutional and legal category

Category	Challenges	Solutions	Country/Region	Reference
Institutional and legal	Lack of proper waste segregation and collection	Reduce the threshold level for the amount of organic waste that waste producers can generate without converting to resources	France	Ingremeau, 2014
		Impose fines for food waste value chain stakeholders who fail to meet government objectives		
		Clear division of labour	China	NDRC, 2010
	Improper waste disposal method	Support/Increase the construction of food waste treatment facilities	China	NDRC, 2010
		Improve collection and transportation capacity to food waste treatment facility		
	Lack of proper standards for waste management	Implement nationwide operational management standards	China	Clercq et al., 2017a

Table 3(i): Summary of the challenges and solutions for economic and resourcing category

Category	Challenges	Solutions	Country/Region	Reference
Economic and resourcing	Poor efficiency in waste segregation and collection	Supply free and different coloured liners for food waste	United Kingdom, Hong Kong	WRAP, 2016; Woon and Lo, 2016; Lo and Woon, 2016
		Provide residual bin stickers and food caddy stickers	United Kingdom	WRAP, 2016
		Sign agreement on waste collection contracts	China	Clercq et al., 2017b
	Challenges in getting a constant supply of feedstock for biogas digester	Target major waste producers (i.e., catering enterprises) and enforce waste segregation at source	China, France, Germany	Clercq et al., 2017a; Juan et al., 2014; LLIE, 2015

Table 3(ii): Summary of the challenges and solutions for economic and resourcing category

Category	Challenges	Solutions	Country/region	Reference
Economic and resourcing	Challenges in dealing with high operational and maintenance costs of the biogas plant	Installation of biogas digester (i.e., anaerobic sequencing batch reactor) with lower operational costs	China	Wang et al., 2022
		Install locally manufactured parts for the biogas plant	South Korea	Kim et al., 2012
	Challenges in dealing with high installation costs of biogas digester	Provide easy loans and tax exemptions	India, South Korea	Yadav et al., 2022; Clercq et al., 2017a
		Provide subsidy based on operational performance rather than subsidising installation costs	China	Clercq et al., 2017b
	Unstable revenue	Provide subsidy to the amount of biogas consumed instead of the amount of biogas produced	Finland	Rasi et al., 2012

Table 4: Summary of the challenges and solutions for technical category.

Category	Challenges	Solutions	Country/Region	Reference
Technical	Challenges in increasing biogas yield	Use multi stages biogas digester	Sweden, Global	Perman et al., 2022; Kiran et al., 2014
		Co-digestion with other types of waste and pre-treatment of food waste	Asia (South Korea, China), Global	Joshi and Visvanathan, 2019; Clercq et al., 2017a; Wang et al., 2022; Ferdes et al., 2022; Kumar et al., 2021; Liu et al., 2012; Vijayakumar et al., 2022; Elgarahy et al., 2023; Singh et al., 2022; Negri et al., 2020
		Optimise operational parameters of the biogas digester	Global	Ferdes et al., 2022
	Challenges in technological maturity	Joint ventures with foreign countries to improve technical skills	Asia	Pandyaswargo et al., 2019
		Increased collaboration between government, universities, and private corporation	China	Clercq et al., 2017a
	Lack of trained manpower	Capacity building and training	India	Yadav et al., 2022
	Challenges in transmitting the energy generated from biogas to the national grid	Decentralised anaerobic digestion system is better at transmitting energy generated to the grid	Asia	Joshi and Visvanathan, 2019

Table 5: Summary of the challenges and solutions for social and cultural category

Category	Challenges	Solutions	Country/Region	Reference
Social and cultural	Poor public awareness towards waste segregation	Conduct regular engagement with the community (door-to-door service)	United Kingdom	WRAP, 2016
	Challenges in encouraging conversion of food waste to biogas among community	Conduct zero waste campaign	Australia	Mahmudul et al., 2022
		Constant socialisation with the community to emphasise the importance of shifting from landfilling/incineration to biogas	India	Pandyaswargo et al., 2019

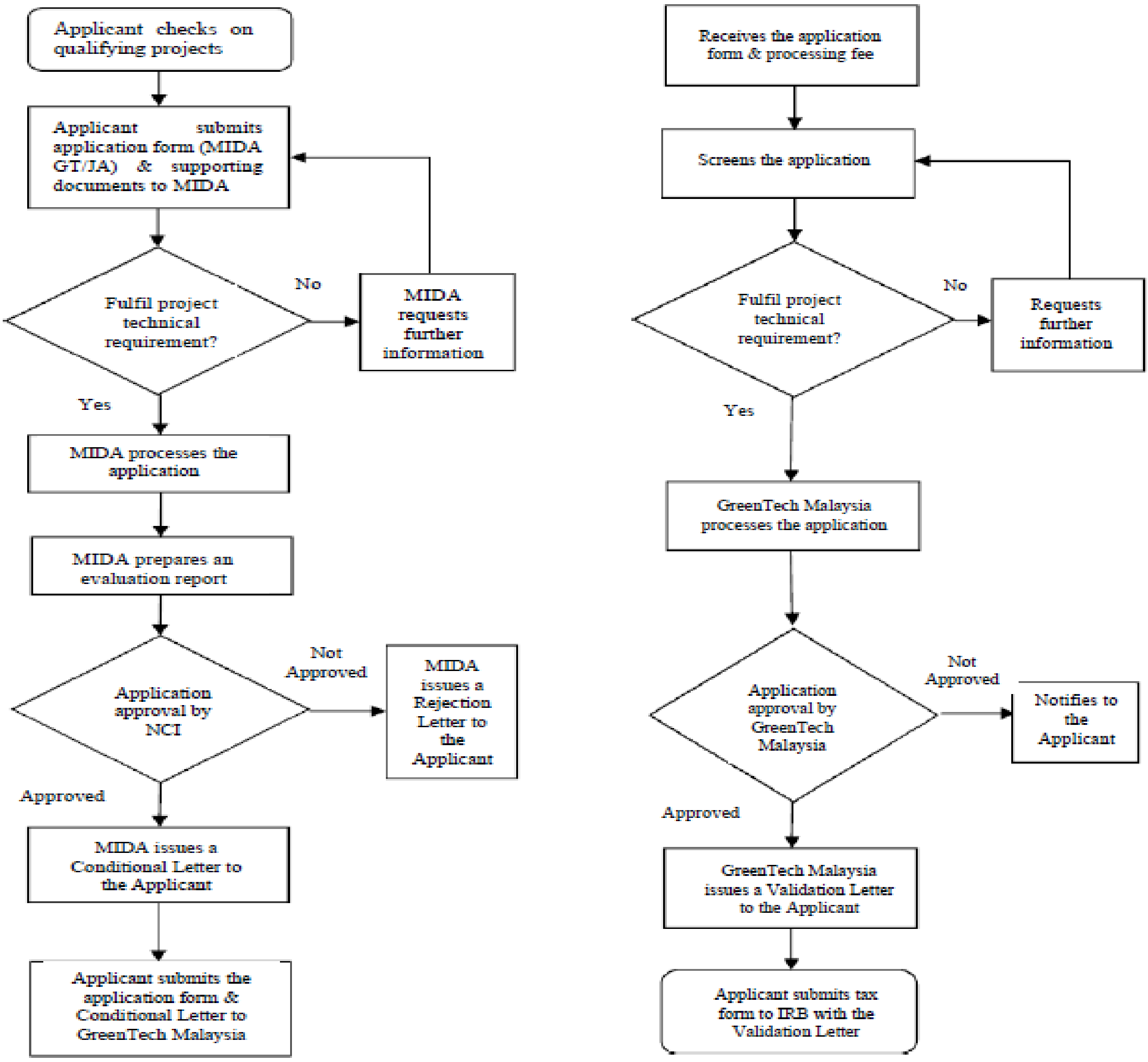

Figure 2: Tax application process in Malaysia (Sharvini, 2020)

Failures in operating the anaerobic digester could result in a lower biogas yield especially when it involves food waste in Malaysia because of its high fat content (Bong et al., 2017). To increase the efficiency and reliability of biogas production from food waste, multiple pretreatments, and co-digestion of other materials with the food waste are essential. Chemical, biological, thermal, and mechanical treatments can be applied according to the composition of the food waste and can result in higher biogas yield. Not only that, multi-stage digesters allow a higher reaction rate compared to single stage digesters, promoting increased biogas generation. In the case of Malaysia, skilled technicians and engineers to operate and maintain the anaerobic digestion plant could be lacking because using anaerobic digester is still an uncommon practice (Ali et al., 2012).

Optimising the conditions of the digester itself plays an important role in ensuring the continuous biogas production necessary for energy generation. The parameters of the digester should be monitored regularly by well-trained staff, coupled with regular skills training and capacity building to upgrade their technical knowledge. This could involve guidance from developed countries or governmental and private corporation with a longer track record of hands-on experience, as well as embedding such training in university curricula of relevant disciplines. Team building, and training should also be conducted regularly in every biogas plant to better understand the operational procedures and conditions of the digester.

Apart from industrial players taking multiple efforts to optimise biogas yields, increasing community awareness is equally important in ensuring successful implementation of food waste-based biogas production for energy generation in any country. Knowledge about biogas technology from the public perspective is limited in Malaysia, while social acceptance of anaerobic digestion is lacking, with people preferring cheaper options over the short term such as fossil fuels heavily subsidised by the government (Khairuddin et al., 2015; Bong et al., 2017). Awareness and a longer-term outlook need to be developed. Key steps in doing this would involve educating the public on the environmental and economic dangers of failing to adapt to renewable energy sources such as anaerobic digestion, building awareness of current technological advancements, and demonstrating the need for and routes to proper waste separation methods, which could result in better waste segregation at source. The concept of zero waste has long been around, and it is more practical to achieve when better food waste management practices are in place. At the same time, other awareness raising would be needed in terms of reducing the generation of food waste altogether.

In Malaysia, the majority of food waste conversion to biogas is only available at lab scale. The initiative to set up and upscale biogas production using food waste as feedstock is hindered in particular by a lack of technical maturity, infrastructure demands, inconsistent feedstock supplies and the initial financial burden. Supporting measures from the government could better help to ease the set-up of anaerobic digester in Malaysia and indeed, will be vital to support system transformation (Bong et al., 2017). It is further evident from the summary in Table 1 that multiple stakeholders need to be involved in efforts to establish anaerobic digestion. Efforts are needed to understand the perspectives of the relevant stakeholders and policymakers to ensure solutions suit the Malaysian context and that they are part of an overall joined up approach towards addressing waste, environmental and sustainability challenges. Participatory co-development approaches are underexplored in the waste-to-energy literature yet are vital if industrial developments are to meet the needs of the end users.

3.7 Practical implications of this literature review

Best practices emerging from the review provide important insights for Malaysia's policy makers. One of the recommended best practices is co-digestion with other types of waste and pre-treatment of food waste. Both public and private sectors should be aware that biogas production can increase with co-digestion of multiple substrates and pre-treatment of food waste. Another best practice is to mandate large waste producers to send their waste to be used for energy production. Targeting major waste producers such as catering enterprises can overcome waste management issues as their food waste will be large in quantity. Bio-waste treatment should be made compulsory for catering enterprises to redirect food waste from landfill into anaerobic digesters. Further, providing proper subsidy mechanisms could help marketize the output. A combination of investment tax allowance, feed-in tariffs, and subsidies could incentivise actions and reduce financial risks. Implementing source separation is another best practice as contamination of food waste with other inorganic matter can obstruct operations. Thus, authorities must encourage waste separation at source to ensure smooth production of biogas using food waste. Finally, it would be important for Malaysia to standardise nationwide operational waste management. Sustainable sector development could be achieved with better performance evaluation systems, supervision mechanisms and nationwide operational management standards.

Future researchers may wish to consider further categories such as political aspects, which were not covered in this study because they did not emerge as important from existing publications. Keywords other than "biogas" AND "food waste" could be used to search through the literature in future work to broaden analysis of the challenges, while analyses could also focus on other countries facing different magnitudes of waste-to-energy challenges. The output of this study will be useful for future researchers seeking to inform policy development in Malaysia, as it can act as a benchmark for other case studies.

4. Conclusion

This paper has reviewed the challenges and opportunities in using food waste-based biogas production for energy generation under environmental, institutional, and legal, economic and resourcing, technical and social and cultural categories, considering the implications and lessons emerging for Malaysia. Overall, our findings underscore that an enabling environment needs to cover three aspects that crosscut the different challenges in each of the categories we considered: i) attitudes, ii) policies, and iii) practices. Options for action that we have put forward link to each of these and can act as key supports for people to take action and succeed, particularly if they are underpinned by effective institutions and well-coordinated governance, both within countries and sectors. The best practices identified are useful for policy makers in Malaysia whose mission is to convert food waste to energy via anaerobic digestion. This study provides a benchmark for further analysis for countries looking into the development of policies to support a sustainable food waste to biogas system.

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