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Treatment of Sewage Sludge Using Anaerobic Digestion in Malaysia: Current State and Challenges

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Anaerobic digestion is widely considered as an environmentally friendly technology for various organic waste including sewage sludge. Although the implementation of anaerobic digestion as an alternative treatment method for sewage sludge can be seen in many countries, its status in Malaysia is not clear. This study reviewed the current state of sewage sludge treatment in Malaysia and discussed the challenges to promote anaerobic digestion in sewage sludge treatment. Other than the common constraints faced, namely technical, political and economic, the characteristics of sewage sludge in Malaysia are considered to be a factor regarding feasibility. Anaerobic co-digestion is the simultaneous anaerobic digestion of two or more substrates which is a promising possible option to overcome the disadvantages of mono-digestion, and improve the economic viability due to higher methane production. There are a variety of biomasses as co-substrates in Malaysia. However, the anaerobic co-digestion of food waste and sewage sludge might be the most feasible method to overcome such constraints. Adding food waste as co-substrate is suggested as the possible approach to not only improve the process's performance but also help to handle the increasing volume of food waste in Malaysia. This study aims to highlight the potential as well as to provide a starting point for further studies regarding the treatment of sewage sludge using anaerobic digestion in Malaysia.

Keywords: sewage sludge, anaerobic digestion, co-digestion, food waste, Malaysia

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INTRODUCTION

Sewage sludge is the residue produced by a wastewater treatment process and has the largest volume amongst all the components removed during the process. In global terms, the amount of sludge is expected to increase. This is due to an increase in the percentage of households connected to central wastewater treatment plants (WWTPs), increasingly tightening regulations on effluent discharges, as well as improved technologies in achieving higher efficiency in wastewater treatment (Werther and Ogada, 1999; Appels et al., 2008). As the sludge itself may contain concentrated levels of contaminants that were initially included in the wastewater, the increasing sewage sludge has become a growing concern. Current primary disposal methods for sewage sludge are agricultural use, landfill, and incineration. Nevertheless, each technique has its particular issues which relate to public health as well as its environmental impacts (Fytili and Zabaniotou, 2008).

Anaerobic digestion is generally considered to be an economical and environmentally-friendly technology for treating various organic waste, including sewage sludge (Appels et al., 2011; Nasir et al., 2012). In the absence of oxygen, the organic waste is biologically degraded and converted into a form of biogas, and other energy-rich organic compounds as end products. The biogas, which is generally composed of 48–65% methane, could be used for power generation (Ward et al., 2008). Since the introduction of both commercial and pilot plant designs during the early 1990s, anaerobic digestion has gained worldwide attention (Karagiannidis and Perkoulidis, 2009). Throughout the world, more than 1,300 anaerobic digestion systems, based on sewage sludge, are in operation or under construction (IEA Bioenergy, 2001). Although China and India lead the initiative among developing countries, the thrust in of the developed world mainly comes from Western Europe (Abbasi et al., 2012). The biogas generation from anaerobic digestion in Europe has reached 4.5–5.0% growth annually, with Germany being the largest biogas producer (Bodík et al., 2011). It is notable that a high proportion of the biogas produced in anaerobic digestion plants is from those situated in WWTPs and thus anaerobic digestion has become a major and essential part in modern WWTPs. The current trend has also seen the introduction of anaerobic co-digestion, in which two or more substrates are mixed and digested simultaneously, with successful examples reported from WWTPs in Denmark, Germany, and Switzerland dedicated to combined sewage sludge and biowaste (Braun and Wellinger, 2009).

As a developing country, Malaysia is no exception from the global *trends* of the volume of sewage sludge increasing annually. It is reported that about 3 million metric tons of sewage sludge is produced annually in Malaysia, and is expected to increase to 7 million metric tons by 2020 (Indah Water Konsortium Sdn Bhd, 2010). Almost 50 % of the sewerage systems in Malaysia uses mechanized plants while others still use septic tanks and oxidation ponds. Some modern mechanized plants have been upgraded with anaerobic digesters whereby the sewage sludge are treated anaerobically to produce CH_4 which is a valuable energy source to generate electricity (Kumaran et al., 2016).

Malaysia is the third-largest consumer of energy in Southeast Asia. Petroleum, natural gas, and coal are the primary fuel sources consumed in Malaysia. In 2014, Malaysia consumed 43% of natural gas, 37% of petroleum and other liquids, 17% of coal, 2% of other renewable, and 1% of hydroelectricity (EIA, 2017). The growing consumption of energy has resulted in becoming increasingly dependent on fossil fuels such as coal, oil, and gas. Fossil fuel depletion and environmental issues have encouraged the government and researchers to investigate renewable energy as alternative sustainable energy resources (Hosseini and Wahid, 2013). Recently, bioenergy sources like animal and agricultural wastes, municipal solid waste and wastewater effluents as the renewable energy sources, have attracted attention and applied for preparing a fraction of the global energy demand (Petinrin and Shaaban, 2015).

The main objective of this study is to assess the potential of treating sewage sludge in Malaysia using anaerobic digestion. The current state regarding sewage sludge in Malaysia was reviewed, with activities around other regions included for comparison. Challenges and tasks faced when treating sewage sludge using anaerobic digestion in Malaysia were discussed, with anaerobic co-digestion which would include food waste, suggested as a possible approach. This study aims to provide a greater understanding as well as a starting point for further study regarding the future aspect of utilizing sewage sludge in Malaysia.

OVERVIEW OF SEWERAGE SYSTEM AND PRODUCTION OF SEWAGE SLUDGE IN MALAYSIA

Malaysia's sewerage industry has expanded over the last half of the twentieth century. At the end of the 1960s, the Malaysian government launched a series of 5-year plans to construct appropriate sanitation facilities in both urban and rural areas. At that time septic tanks were used as the primary sewerage system. In the 1970s, the government started the "National Sewerage Development Program" to develop sewerage facilities in major cities with the aim of introducing modern sewerage systems in urban areas. During the 1980s, the government introduced a policy that obliged housing developers to build sewerage systems for regions comprising more than 30 households of a 150 population equivalent (PE). This resulted in the diffusion of many small-scale wastewater treatment facilities all over the country, which were gradually connected to large-scale sewerage systems to complete the public sewerage system (Japan Sanitation Consortium, 2011). A profile of sewerage systems in Malaysia can be seen in **Table 1**. Although the large-scale sewerage systems, or public sewage treatment plants in Malaysia have increased in number, as seen from **Table 1**, the amount of operational individual septic tanks constitutes an enormous part of the overall wastewater treatment in Malaysia. This current situation could be a crucial factor in the attempt to utilize sewage sludge, as the septic tanks only provide partial treatment of the sewage that flows into it and needs to be desludged on a regular basis (Suruhanjaya Perkhidmatan Air Negara, 2017).

Under the Environmental Quality (Scheduled Waste) Regulations 2005, the Department of Environment (DOE) categorizes sludge generated from WWTPs as scheduled waste, and shall be disposed of under a prescribed premise only. Since 1994, the management of wastewater in most of the states of Peninsular Malaysia, is undertaken by a private company named Indah Water Konsortium (IWK) Sdn Bhd. According to a recent sustainable report by IWK, it has been operating and maintaining 16,328 km of sewer pipelines, 5,997 public sewerage treatment plants and 926 network pump stations. On average, IWK assumes control of 300 treatment facilities and 1,000 km of sewer network yearly (Indah Water Konsortium Sdn Bhd, 2013). It was estimated that the total cost of managing sewage sludge is US$ 0.33 billion per year (Kadir and Mohd, 1998). Currently, the sewage sludge is commonly being disposed of either at landfill sites or being burned in incinerators (Bradley

TABLE 1 | Profile of sewerage systems in Malaysia.

Sewerage facilities	2015		2016	
	Quantity	Population Equivalent (PE)	Quantity	Population Equivalent (PE)
Public sewage treatment plant (a + b)	6,571	23,517,185	6,752	24,789,450
a. Multipoint plant	6,481	16,296,052	6,659	16,964,923
b. Regional plant	90	7,221,133	93	7,824,527
Private sewage treatment plant	3,158	2,795,877	3,338	3,009,095
Communal septic tank	4,386	532,051	4,386	532,076
Individual septic tank	1,321,856	6,747,774	1,343,439	6,859,823
Traditional system	1,369,609	6,848,045	1,154,592	5,772,960
Network pumping station	1,078	n.a.	1,117	n.a.
Length of sewer network (km)	18,689	n.a.	18,689	n.a.

n.a., Data not available.

and Dhanagunan, 2004). However, as mentioned before, the sewage sludge itself may contain particular contaminants, and in case of incineration, approximately 30% of the solids remain as ash. Hence, these current disposal methods remain a concern (Malerius and Werther, 2003).

IWK had begun planning to reuse the sewage by-products, yet this mainly occurs only at local plants with a PE of 100,000 (Kadir and Mohd, 1998). There are very few wastewater treatment plants where digestion system could be found operating, and in most cases, the biogas produced is not utilized for power generation but only for combustion (Liew, 2008; Indah Water Konsortium Sdn Bhd, 2013). Bunus Centralized Sewage Treatment Plant (Kuala Lumpur) generates 2,500 m^3/days of biogas. From that amount of biogas, 15,000 kWh/m^3 of power without conversion losses could be produced. In fact, to date, all methane gas has been burned without effective use. As the average plant consumes electricity of 43,503 kWh/day (David et al., 2014), which is about 40% of the overall operations and maintenance costs (Baki et al., 2005), then the power generated through biogas from anaerobic digestion could be helpful in reducing total energy consumption, as well as serving as an alternative power generation source for public use. Recently, Malaysia has three modern WWTPs which are equipped with anaerobic digestion. There are the Pantai 2 WWTP in Greater Kuala Lumpur, the Jelutong WWTP in Pe18nang, and the Langat WWTP in Selangor. Pantai 2 and Jelutong WWTP are in operation, but at Langat is due to be completed in 2018. Pantai 2 WWTP has been designed to produce up to 9,600 m^3/day of biogas. Presently, in 2018, they produce around 450–500 KW electricity (Pantai 2 regional sewage treatment plant Kuala Lumpur)[1]. The Jelutong WWTP is one of the largest plants in Malaysia. It operates to treat 800,000 PE (Jelutong WWTP-Malaysia).[2]

Overall, not many investigations or studies have been conducted in Malaysia regarding the treatment of sewage sludge using anaerobic digestion, which reflects that the focus and awareness of these issues are indeed not high amongst the general public.

TREATMENT OF SEWAGE SLUDGE USING ANAEROBIC DIGESTION

Anaerobic digestion is a proven technology for sewage sludge treatment, in which the high water content sewage sludge can be processed without any pretreatment (Ward et al., 2008). The properties of sewage sludge are modified during anaerobic digestion, with not only biogas being produced as a result, but also several positive consequences for the sludge management that follows the process. Anaerobic digestion enhances the stabilization of sewage sludge, reduces pathogens and odor emission, and dry matter of sludge is reduced, which leads to a significant reduction in the final sludge volume. These benefits of anaerobic digestion of sewage sludge are widely recognized, and the technology is well established in many countries. The total biogas production in several countries and biogas production from WWTPs are listed in **Table 2** based on the statistics of the International Energy Agency (IEA Bioenergy Task 37, 2017) and the World Bioenergy Association (2017). Germany dominates the worldwide biogas production with 10,431 biogas plants generating 55,108 GWh/y of electricity. It has 1, 258 sewerage plants generating 3,517 GWh/y of electricity. Although India has 83,540 biogas plants, bioenergy production is still at a household mode and has been limited to small size biogas plants which are used by the people especially in rural areas. On the other hand, in Malaysia, IWK has taken over 4,281 small plants for upgrading to large plants by 2013. Overall IWK has 35 large plants (Indah Water Konsortium Sdn Bhd, 2013) which is 247 GWh/y electricity generated in 2017 (Sustainable Energy Development Authority Malaysia, 2018)[3].

Meanwhile, in Japan, policies such as SPIRIT21 (Sewage Project, Integrated and Revolutionary Technology for Twenty First Century) and Sewerage Vision 2100 have been implemented over the last decade regarding the improvement of WWTPs and utilization of sewage sludge. Led to the active movements on the usage of sewage sludge, which included energy recovery by anaerobic digestion. According to the Japan Sewage Works Agency, 280 out of 2,150 WWTPs have anaerobic digestion system operating, with 0.4–0.6 m^3 CH_4/kg-VS produced averagely (Japan Ministry of Land, Infrastructure, Transport and Tourism).[4] One of the most successful WWTPs has sewage sludge treated using anaerobic digestion and is located in Yamagata Prefecture. The daily biogas produced is 4,082 m^3, in which 7,226 kWh/d of electricity is generated. This corresponds to 48.7% of the total energy consumption of the plant itself (Li and Kobayashi, 2010).

[1]English brochure. Published by IWK.
[2]Available online at: http://sfcu.at/portfolio_category/asia/?lang=en
[3]Available online at: http://www.seda.gov.my/
[4]Available online at: http://www.mlit.go.jp/index_e.html

TABLE 2 | Biogas production in several countries.

Country	Year	Total biogas production (From agricultural residues, industrial wastewater, bio-waste, landfills and sewage sludge)		Biogas production in WWTPs (Only from sewage sludge)	
		Number of plants	[GWh/y]	Number of plants	[GWh/y]
Australia	2017	242	1,587	52	381
Austria	2017	291	3,489	39	18
Argentine	2016	62	n.a.	n.a.	n.a.
Belgium	2015	184	955	n.a.	n.a.
Brazil	2016	165	5,219	10	210
China	2014	11,500	90	2,630	n.a.
Czech Republic	2015	554	2,611	n.a.	n.a.
Denmark	2015	156	1,763	52	281
Finland	2015	88	623	16	152
France	2017	687	3,527	88	442
Germany	2016	10,431	55,108	1,258	3,517
India	2015	83,540	22,140	n.a.	n.a.
Ireland	2015	28	202	n.a.	n.a.
Italy	2015	1,491	8,212	n.a.	n.a.
Japan	2015	n.a.	30,200	2,200	n.a.
Norway	2017	39	738	24	223
Korea	2016	110	2,798	49	1,234
Pakistan	2015	4,000	n.a.	n.a.	n.a.
Poland	2015	277	906	n.a.	n.a.
Switzerland	2017	634	1,409	475	620
Spain	2015	39	982	n.a.	n.a.
Sweden	2017	279	1,200	139	n.a
Sri Lanka	2013	6,000	n.a.	n.a.	n.a.
Thailand	2014	n.a.	1,500	n.a.	n.a.
Netherlands	2015	268	3,011	80	541
United Kingdom	2016	987	26,457	162	950
United States	2017	2,100	1,030	1,240	n.a.
Malaysia	2017	n.a.	482	35	247

n.a., Data not available.

CHALLENGES TO UTILIZE SEWAGE SLUDGE USING ANAEROBIC DIGESTION IN MALAYSIA

Technical, Political and Economic Issues for Sewage Sludge Anaerobic Digestion

Several issues are surrounding the water services industry that needs the attention of policymakers and stakeholders to ensure the success of restructuring the water industry and achieving the goal of a sustainable water services industry in Malaysia. Anaerobic digestion is a complex system which involved several stages of biotransformation of organic matter, which are hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Each of these steps has operational requirements, especially for methanogenesis, where methanogenic bacteria convert acetate into CH_4 and CO_2. In term of the technical aspect, improper operation of the anaerobic digestion will lead to low biogas yield. Sun et al. (2014) showed that increasing fat content in municipal solid waste ($< 60\%$) could increase CH_4 yield significantly. The study also observed a decrease in CH_4 yield when the fat content is higher than 65% and displayed inhibitory effect on biogas production. There is still a lack of research and development effort in this aspect. Besides, the operation and maintenance of the anaerobic digestion plant will require skillful engineers and technicians, which could be lacking in Malaysia as anaerobic digestion is still not a common practice (Ali et al., 2012).

Climate change and depletion of fossil fuel along with the rise in petroleum prices have forced the Malaysian Government to rethink strategies to be more effective including the decision to embark on renewable energy resources as a better energy source amongst the global energy mix. The Malaysian Government established policies, renewable energy programs, and incentives more effective to promote and develop the use of renewable energy. In 2000, under the eight Malaysia Plan (MP), the Fifth Fuel Diversification Policy was launched, and Renewable Energy was included to be the fifth primary energy source, following oil, gas, coal, and hydropower. Following this, there has been continuous implementation of renewable energy-promoting policies and actions, such as the Small Renewable Energy Program, National Green Policy 2009, National Renewable Energy Plan 2010, Renewable Energy Act 2011, Feed-in Tariff (FiT) mechanisms, renewable energy business fund and Green Technology Financial Schemes under different Malaysia Plans (Bong et al., 2017). On the other hand, regarding social aspect, the public is generally not aware of anaerobic digestion plant and can be reluctant to have the anaerobic digestion plant near residential area and city area.

Characteristics of Sewage Sludge in Malaysia

Despite producing a massive amount of sewage sludge annually, the utilization of sewage sludge in Malaysia did not get as much attention or progress as seen in other regions. The current state of sewage sludge treatment sees it primarily being used for landfill. Several studies had reported using sewage sludge to produce clay bricks (Liew et al., 2004), compost (Kala et al., 2009), as well as fuels (Abbas et al., 2011). Nevertheless, there are very few focused on anaerobic digestion. One aspect that should be considered regarding anaerobic digestion is the characteristics of sewage sludge. Characterization of sewage sludge is essential for determining a suitable rate of application of sewage and for investigating pollutant risks that may be associated with the use of sewage sludge. Sewage sludge is characterized by high concentrations of solid and organic matter, with a significant presence of pathogens, nutrients, organic and inorganic pollutants. In an anaerobic digester, proper carbon to nitrogen (C/N) ratio is essential for efficient digestion (Kim et al., 2012). Characterization of sewage sludge from wastewater treatment plants in Malaysia can be seen in **Table 3** (Abbas et al., 2011). The C/N ratio of sewage sludge is 6. However, in general, the suggested optimum C/N ratio for anaerobic digestion is in the range of 20–30 (Parkin and Owen, 1986), but the C/N ratio of sewage sludge is ranged between 6 and 16 typically (Tchobanoglous et al., 1993). Similar research also reported by Rosenani et al. (2008) in which they analyzed sewage sludge samples taken from 10 WWTPs throughout Peninsular Malaysia, showed that the C/N ratio of sewage sludge ranged from 4.1 to 38.0 with a mean of 16.6. As the fermentation substrate, this low C/N in sewage sludge, which goes against the nutrition balance of microorganisms. The pH of sewage sludge was reported as acidic, ranging from 3.57 to 6.43 because no lime was added in WWTPs. While the optimum pH of anaerobic digestion is in the range 6.5–7.5 (Liu et al., 2008).

Besides, the concentration of nutrients, such as nitrogen, phosphorus, iron, nickel, etc., it is crucial as the bacteria needs them for optimum growth. Although these elements are needed in low concentrations, the lack of these nutrients interferes microbial growth and performance. Methanogenic archaea have relatively high internal concentrations of iron, nickel, and cobalt, which are 1,800, 100, and 75 mg/kg, respectively (Rajeshwari et al., 2000). Rosenani et al. (2008) determined the mean of the heavy metal content (mg/L) of 10 selected sewage sludge samples taken from different wastewater plants in Malaysia and found that elements like potassium, magnesium, iron and nickel were at significantly lower levels than the suggested concentration. Therefore, precise design and a good understanding of the anaerobic digestion process would be necessary to apply the process based on the different characteristic of each WWTPs sewage sludge.

On the other hand, Baki et al. (2005) reported that 85% of the WWTPs are serving <5,000 PE. Therefore, the volumes generated from those small size treatment plants might be too small to be considered for power generation, and even if the sludge were to be collected to one centralized location, it would be uneconomical concerning logistics and transportation costs. Under such circumstance, studies based on the small-scale WWTPs seen in Germany could be used as a reference when adopting anaerobic digestion in small-scale WWTPs in Malaysia (Dichtl et al., 2013). Therefore, the results determined may indicate that the current state of sewage sludge currently would be considered as low feasibility if anaerobic digestion is applied. To cope with the challenges mentioned above, more detailed studies as well as a different approach are needed.

Anaerobic Co-digestion of Sewage Sludge

The complex microstructure components such as extracellular polymeric substances make sewage sludge difficult to hydrolyze and digest. These components have low volatile solid degradation (30–50%) even at a long retention time (20–30 day), caused low methane yield (Appels et al., 2008; Pereira et al., 2015). To accelerate the hydrolysis and enhance subsequent methane productivity, a variety of sewage sludge pretreatment options, such as mechanical, thermal, chemical, biological process or integration of these, have been developed at laboratory or pilot level recently (Kim et al., 2010; Houtmeyers et al., 2014; Kinnunen et al., 2015; Zhen et al., 2017). Although pretreatment can increase methane yield but leads to high energy demand and capital cost, complex operation, and maintenance, as an aspect of uneconomically feasible, caused most of them were still in the research stage and could not be utilized in real or commercial scale.

Anaerobic co-digestion is the simultaneous digestion of a homogenous mixture of two or more substrates. By combining two or more substrates or biomass resources, anaerobic co-digestion could improve the economic viability of anaerobic digestion plants due to higher methane production (Alvarez et al., 2000), and hence is a well-known and feasible option to overcome the drawbacks of a conventional digestion process. Co-digestion can improve the C/N ratio, enhance biogas production, overcome the nutrient imbalance of substrate, and improve the stable condition of anaerobic digestion (Kumaran et al., 2016). Anaerobic co-digestion of sewage sludge with biomasses resources which is a municipal solid waste, livestock manure, industrial waste, forestry, and agriculture waste can be used as co-substrate in anaerobic co-digestion. Recently, different organic waste materials such as food waste with higher content of organic carbon have been mixed with sewage sludge in anaerobic co-digester to improve C/N ratio which is leading to an increase in biogas production (Tanimu et al., 2014).

Anaerobic co-digestion between sewage sludge and the organic fraction of municipal solid waste (OFMSW) is the most reported co-digestion research (Alvarez et al., 2014). It was found that the cumulative biogas production from mixtures of sewage sludge and the OFMSW increased with increasing proportions of the OFMSW (Sosnowski et al., 2003). One study which evaluated the economic and environmental suitability of using OFMSW as co-substrate in two WWTPs had concluded that using OFMSW as co-substrate with sewage sludge was the most advantageous solution when compared to OFMSW composting and conventional digestion (Krupp et al., 2005).

The introduction of anaerobic co-digestion would be an advantageous approach to the current situation of OFMSW treatment in Malaysia as well. Nearly half of the Malaysian municipal waste is made up of food waste, and by 2020 the amount of municipal waste is estimated to increase to 9,820,000 tons in Peninsular Malaysia only (Tarmudi et al., 2009). Conventionally this municipal waste is disposed through landfill, but most of the landfill sites are mere open dumpsites where capacity has been exceeded. The high amount of food waste at landfill sites would lead to issues such as foul odor, toxic leachate and vermin infestation (Lee et al., 2007). There is currently no

TABLE 3 | Characteristics of sewage sludge in Malaysia.

Moisture content (%)	Volatile matter (%)	Fixed carbon (%)	Ash content (%)	C (%)	N (%)	C/N	H (%)	S (%)	Heating value (MJ/Kg)
12	48.86	19.32	31.86	33.01	5.52	6	4.97	1.18	15.7

clear strategy regarding the increasing food waste in Malaysia. Thus, the co-digestion of sewage sludge and food waste might be the most feasible breakthrough method for handling both biomass resources problems in Malaysia. In this case, WWTPs with low PE could be benefited by including food waste collected from the surrounding area. A well-organized system or structure that includes collection and separation of municipal solid waste would certainly lead to a more feasible anaerobic digestion process of sewage sludge.

CONCLUSIONS

This this study we reviewed the current state of sewage sludge treatment in Malaysia and discussed the challenges to promote anaerobic digestion in sewage sludge treatment. Currently, the sewage sludge produced from WWTPs is mostly disposed of through landfill and incineration. Although noteworthy movements can be seen in many regions including developing countries, where sewage sludge is utilized using anaerobic digestion for energy recovery as well as alternative to replace conventional methods, the focus on sewage sludge within Malaysia is not strong. The increasing volume of sewage sludge produced, corresponding with the growth of population, should not be treated lightly as the process itself consumes a lot of energy. Furthermore, the majority of WWTPs in Malaysia are operated on a small scale, and so the feasibility of anaerobic digestion, if applied, would be a challenge. Though various technical, political, and economic factors constrain anaerobic digestion of sewage sludge, the anaerobic co-digestion of food waste and sewage sludge might be the most feasibility method to overcome such constraints. It would not only improve the performance of anaerobic digestion when applied on sewage sludge but also simultaneously solve the problem of the increasing food waste in Malaysia. Nevertheless, considering the lack of information as well as the complexity of anaerobic digestion itself, more research, especially with some demonstration projects, are needed to verify the proper design, suitable conditions, and practical approach for the utilization of sewage sludge using anaerobic digestion in Malaysia.

Overall anaerobic digestion is a proven technique and at present applied in a variety of waste streams. To cope with the increasing energy demand, as well as to mitigate the environmental impacts as a result of the present situation, immediate but effective actions have to be taken, both by the government and the private sectors in Malaysia. Promotion and application of utilizing sewage sludge using anaerobic digestion could be not only one of the solutions to various environmental problems, but also a breakthrough in the field of waste recycling for Malaysia, where the accumulation of knowledge and understanding about anaerobic digestion could be shared and used for other biomass resources.

AUTHOR CONTRIBUTIONS

FH and LY carried out the literature review and wrote the initial draft. HA, YA, and TY revised the manuscript. HK and HD revised the manuscript and provided over-all guidance for work and editing of the text.

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