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Review

Biogas Harvesting from Organic Fraction of Municipal Solid Waste as a Renewable Energy Resource in Malaysia: A Review

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Abstract

The accumulation of organic fraction in municipal solid waste (OFMSW) is now becoming scarce globally due to population and economic boosts, especially in Malaysia. Municipal solid waste (MSW) landfills remain the predominant end-state for waste disposal in most developing countries. Unsustainable MSW management accelerates environmental degradation through landfill gaseous (LFG) emissions of mainly methane (CH_4) and carbon dioxide (CO_2), which promote global warming that finally is affecting human health. Recently, harnessing CH_4 from anaerobic digestion of solid waste has attracted more interest and promised betterment in MSW management. With its current amount of more than 50%, organic material in landfills is estimated to emit 310,225 CH_4/year with carbon credit of US$ 85.93, which can potentially generate 2.20×10^9 kWh of electricity valued at US$ 220 million. This present work is a review manuscript that discusses the state-of-the-art anaerobic digestion of OFMSW as treatment in term of waste diversion from a landfill. The study also estimates the renewable energy potentials from OFMSW waste diversion. Finally, this paper discusses the benefits of harnessing biogas from the perspectives of environmental benefits, energy recovery, and economics.

Keywords: anaerobic digestion, biogas, carbon capture, environmental remediation, environmental biotechnology, waste treatment, waste minimization

Introduction

Solid waste management (SWM) has attracted global attention with the average generation rate in 23 developing countries reaching 77 kg/person/day and continuing to expand [1]. With current world population growth, it is approximated that the load of municipal solid waste (MSW) generated by the year 2020 is about nine million tons/year. Furthermore, estimation on the national recycling rate is about 3-5%, and the waste generation rate for Malaysia is 4.3% per annum for 10 years [2]. MSW is mainly introduced by households, and commercial and industrial sectors from the accumulation of community exertion in metropolitan areas. Peninsular Malaysia generated MSW of almost 17,000 tons/day (6.2 million tons/year) in 2002, an amount that is increasing annually

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[3]. Currently, the MSW generation rate in Malaysia has attracted considerable attention; hence sustainable waste disposal is one of the major environmental issues faced by local authorities [4].

A landfill is always the best disposal method in developing and developed countries due to its economically simple management. For example, in Australia and the United States of America, local authorities manage more than 2,000 existing landfills nationwide. Although land filling offers an economical waste disposal method, tremendous increase in waste disposal (especially organic waste) can accelerate environmental degradation through air and water pollution if not managed properly. MSW contains organic materials as its largest portion, which also is known as putrescible waste, which produce gaseous emissions called landfill gas (LFG), such as methane (CH_4), carbon dioxide (CO_2), and other gas elements through the decomposition process [5]. In addition, the main content of the LFG is CH_4, which can become a major greenhouse contributor for the approximately 5% of the global greenhouse gaseous GHG budget, as CH_4 is 21 times more hazardous than CO_2 [6]. The consequence of these GHG emissions is the phenomena of global warming [7]. Furthermore, a high percentage of moisture content in organic waste advances leachate production which, in turn, contributes to serious water pollution.

Recently new emerging wastes to energy (WtE) concepts are encouraging in terms of offering electricity, heat, transport, and fuel. Harvesting biogas from landfill gas generated from the anaerobic digestion of OFMSW may have potential as a substitute alternative transport fuel and as a significant means of treating organic fractions of municipal solid waste (OFMSW) [8]. In the meantime, Malaysia has focused on sanitary landfills equipped with gas recovery systems. The increased production of MSW accompanied by the environmental and economic difficulties has resulted in great efforts to find alternative methods of disposal [9]. Thus, the WtE concept is gaining more interest in the search for such renewable energy sources as biogas production (CH_4 and CO_2) [10]. The benefit of the biogas process is the opportunity to use organic constituents from the organic waste fraction and to generate electricity, which is relatively manageable and clean. The greatest advantage to adopt this technology is the insurance of the environmentally friendly aspect of technology, including the potential for the complete recycling of minerals, nutrients, and fibrous (cellulosic) materials.

Previous attempts initially focused on the anaerobic digestion of MSW for bioenergy production over a decade ago [11-14]. Anaerobic digestion is one of the waste treatments that promise an acceptable solution to reduce and stabilize the OFMSW volume prior to sustainable landfill management [15]. Anaerobic treatment is also classified as a robust biochemical conversion mechanism and is extensively practiced. Lately, the practice of anaerobic digestion for the treatment of organic waste has emerged spectacularly and the amount of anaerobic-digested substrate from organic waste has increased at an annual growth rate of 25% [16]. Accordingly, the transition to sustainable renewable energy practices should be encouraged prior to the improvement in landfill management, especially in respect to the anaerobic digestion of OFMSW to promote biogas production. This present work is a review manuscript that discusses the state-of-the-art anaerobic digestion of OFMSW as treatment in terms of waste diversion from a landfill. The study also estimates the renewable energy potentials from OFMSW waste diversion. Finally, this paper discusses the benefits of harnessing biogas from environmental benefits, energy recovery, and economic perspectives.

Organic Fraction of Municipal Solid Waste Generation in Malaysia

The rate of waste in Malaysia is accumulating, which covers the main community activities that are from 0.45-1.44 kg/capita/day [17]. An earlier study reported the average amounts of MSW generated in Malaysia were 0.5-0.8 kg/person/day, which has increased to 1.7 kg/person/day in major cities [18]. Currently, an average of 2,500 tons of MSW is collected every day for Malaysia's capital, Kuala Lumpur [19]. A different study reported that Malaysia produces 1.5 kg/capita/day MSW, which presents major challenges for MSW management [20]. With this generation rate, the Ministry of Housing and Local Government (MLHG) is currently facing problems and difficulties in regards to having effective and greener methods for MSW disposal [21]. A review revealed the idea that increases in human population and activities in turn results in the rise of waste generation [22]. The large percentage of biodegradable material such as food waste contributes a favourable environment for landfill gas emissions, which has been attributed to tremendous population growth, rapid urbanization, economic growth, and the multi-racial aspects of society [23].

An overview shows a tremendous upward trend on waste generation from 1997 and is projected to increase until 2020 [24]. Table 1 explains annual waste generation in Malaysia by each state summarized from studies. From the projection, Selangor was the major MSW generator and with this waste generation rates make MSW management crucial. MSW generation in 2010 was 8.196 million tons, and estimated values for 2015 and 2020 are 9.111 million tons and 9.820 million tons, respectively, which helps predict the future construction and landfill lifespan [25]. The Ninth Malaysian Plan estimated that about 45% of the future waste will made up of food waste (24%), plastic (7%), and paper (6%), and other minor components will consist of glass and metals. Organic waste is explained as food waste, including uneaten food and food preparation leftovers from the residence [26]. Waste characterization is important in order to decide the best alternative management and for technology implementation [27]. Characterization also allows designing programs to divert recyclables and compostable materials from landfills. Characterization of MSW in Malaysia by different

Table 1. MSW generation by states in Peninsular Malaysia (in thousands of tons).

State	1998	1999	2000	2010	2015	2020
Kuala Lumpur	1,058	1,070	1,082	1,202	1,262	1,322
Selangor	1,169	1,204	1,240	1,595	1,773	1,950
Pahang	202	206	210	250	270	290
Kelantan	123	126	120	87	72	42
Terengganu	119	122	125	155	170	185
Negeri Sembilan	267	278	291	411	471	531
Melaka	208	216	225	310	353	395
Johor	927	956	1,005	1,395	1,590	1,785
Perlis	28	28	29	34	36	39
Kedah	569	569	631	941	1,096	1,251
Penang	611	611	648	833	925	1,018
Perak	719	719	763	983	1,093	1,021
Total	6,000	6,105	6,369	8,196	9,111	9,820

Forecasting based on (1998-2010) average increase rate of 2.14%.

researchers is described as in Table 2 [28-31]. Table 2 summarized the changing pattern of waste generation in Malaysia. The Food and Agriculture Organization (FAO) of the United Nations (UN) found that one third (1.3 billion tons) of yearly food production for human supply is dumped as waste into landfills [32]. Food waste is the single-largest component of the waste stream by weight in Malaysia. Moreover, organic waste generated from fruits and vegetables also is high and becoming a source of concern in landfill management due to its high biodegradability and increased according to the following years [33]. The organic fraction varies greatly, and that generated from rural areas is slightly different compared to urbanized areas. The compositions always follow through seasonal changes, lifestyles, and cultures, which influence recycling practices and the type food waste generated.

Table 3 describes waste composition in wet and dry analysis. Malaysian MSW contains a very high concentration of organic waste, and consequently has a high moisture content (55.05%) and bulky density above 200 kg/m^3 [34]. The MSW profile and information on the quantity of solid waste generated is fundamental to almost all aspects of SWM. Hence, indiscriminate decomposition of this organic waste results in large-scale contamination of land, water, and air – probably from MSW wastewater or so-called leachate [35]. OFMSW disposal enhances ecological problems that have been brought to light as a result of an increase in public health concerns and environmental sustainability issues [36].

In Korea, where food waste as the major organic constituent in MSW as the main source of decay, odour, and leachate, landfill disposal has been prohibited [37]. The country practices waste separation at source and transported to recycling facilities for composting production and animal feed. However, the demand for fertilizer and soil amendment is very low. Most of the organics contained in food waste are discard as secondary wastewater [38]. Fig. 1 indicates the recyclable components in Kuala Lumpur during 2005 and is expected to increase each year [39]. A straightforward interpretation from the Fig. 1 proved that food waste has the largest fractions that supply sufficient material for recyclable activities.

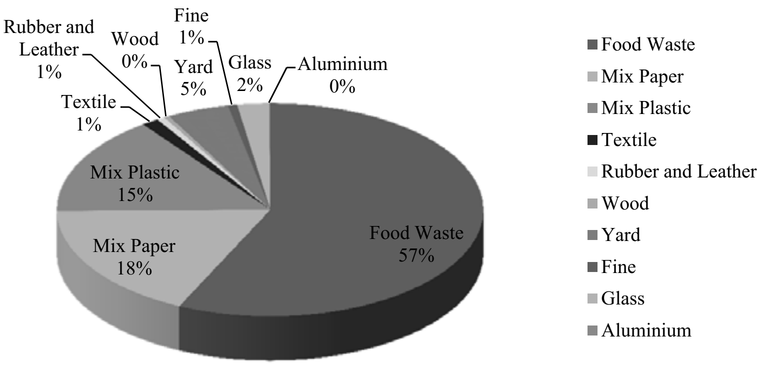

Fig. 1. Recyclable Components in Kuala Lumpur in 2005.

Table 2. Characterization of MSW by different researchers (%).

Material \ Reference	[28]	[19]	[29]	[30]	[31]
Food	68.67	38.42	56.80	37.43	46.94
Mix paper	11.45	17.75	16.50	16.78	17.89
Mix plastic	6.43	20.04	15.30	18.92	20.28
Textile	1.50	3.55	1.30	8.48	-
Wood	0.70	1.39	0.40	3.78	-
Yard waste	-	1.12	4.70	3.18	-
Rubber and leather	-	1.78	0.60	1.32	0.17
Glass	1.41	4.09	1.20	2.68	2.60
Organic fines	-	0.98	0.70	4.37	-
Aluminium/metal	2.71	3.30	2.50	3.40	4.31
Others	7.13	7.58	-	7.16	7.81

Table 3. Characteristics of Kuala Lumpur MSW composition.

Proximate analysis (wet)	Weight (%)
Moisture content	55.01
Volatile matter content	31.36
Fixed carbon content	4.37
Ash content	9.26
Elemental analysis (dry)	
Carbon content	46.11
Hydrogen content	6.86
Nitrogen content	1.26
Oxygen content	28.12
Sulphur content	0.23
Heavy metals (dry)	Ppm
Chlorine	8.84
Cadmium	0.99
Mercury	0.27
Lead	26.27
Chromium	14.41
Other parameters	
Bulk density (kg/m^3)	240.00
Net calorific value (kcal/kg)	2,180.00

Landfill Management in Malaysia

Landfill Facilities

In Malaysia, MSW deposits about 95% of all generated waste in landfills, while less than 10% of these landfills are sanitary [40]. This proportion is increasing and encourages more open dumping. Landfills have become the main waste disposal method because incinerator technologies for waste disposal are inefficient due to typical high moisture content in organic waste of MSW [41]. However, having landfills as a disposal method has become a concern due to the amount of waste produced and the limited number of available sites for new landfills and high land pricing. Moreover, the increasing amount of waste being dumped is expected to burden the environment and water resources through environmental pollution and water resource contamination by landfill leachate. According to the Department of Solid Waste Management (2012) in Malaysia, river water quality is decreasing in proportion with the increase of illegal dumpsites. These landfills ought to be improved for sanitary landfill management. In most developing countries such as Singapore they aimed to reduce landfill waste disposal and successfully disposed of less than 10% of waste generated to the only landfill, which is Semakau landfill. About 40% of the waste is recycled and incinerated, while in the U.S. on 2010, 29.07% of generated waste was recovered, 5.3% was composted, 14.5% was incinerated, and 50.5% was landfilled.

In 1988 there were only 49 landfills in operation in Malaysia. The trend of landfill operations was 155, 161, 176, and 296 landfills for 2001, 2002, 2007, and 2011, respectively [42]. Today there are 166 in operation while 130 have been closed. Table 4 estimates the distribution of the numbers of operational and non-operational landfill sites in Malaysia obtained from JPSPN (2005) [43]. The landfills vary in operational capacities 8-60 hectares [44].

Most of the landfill facilities are mere open dumpsites with operational capacities. Malaysia has two classification systems for landfill sites. The first is based on the decomposition processes within the landfill and is classified as an anaerobic landfill (anaerobic sanitary landfill with daily cover, improved sanitary landfill with buried leachate collection pipes, or semi-aerobic landfill with forced aeration). The second classification is based on operational purposes, where it is labeled as Level 1, the tipping control; Level 2, sanitary landfill with embankment and daily soil cover; or Level 3, sanitary landfill with leachate treatment system.

There are only 10 sanitary landfills in Peninsular Malaysia, and four are in Sarawak. The waste fractions disposed of by sanitary landfill (SLF) and dump site (DS) were found to be 28.3% and 71.7%, respectively, as reported in Table 5. The Japanese International Cooperation Agency (JICA) and Ministry of Housing and Local Government (MHLG) claim that 29 of 64 landfill sites visited by the JICA team were not registered in the MLHG list of landfill sites.

Existing Landfill Status in Malaysia

Landfill facilities in Malaysia are mismanaged in terms of landfill gas management and leachate treatments. MSW contains high amounts of organic waste that generate vari-

Table 4. Distribution of landfills in Malaysia.

State	Landfills in operation	Landfill not in operation
Johor	13	21
Kedah	10	5
Kelantan	13	4
Melaka	2	5
Negeri Sembilan	8	10
Pahang	19	13
Perak	20	9
Perlis	1	1
Pulau Pinang	1	2
Sabah	21	1
Sarawak	51	12
Selangor	6	12
Terengganu	9	12
FT Kuala Lumpur	1	7
FT Labuan	1	0
FT Putrajaya	0	0
Total	176	114

FT – Federal Territory

ous gases when dumped, compacted, and covered in landfill. Anaerobic bacteria thrive in the oxygen-free environment, resulting in decomposition of the organic materials and the production of carbon, CO_2, water, and heat for the aerobic process, and biogas (CH_4 and CO_2) for the anaerobic process [45]. CO_2 is possible to percolate from the landfill due to its solubility in water. CH_4, on the other hand, has different physical characteristics, which are less soluble in water and lighter than air; this causes CH_4 to migrate out from the landfill sites and be vented to the atmosphere. The transmission of CH_4 from landfills is continually arising due to the increasing population growth and waste generation per capita [46]. It has been revealed that landfills rank as the third-largest anthropogenic CH_4 source after rice paddies and ruminants [47]. Other efforts have been made to classify landfills as the major source of CH_4 emissions (53%) in Malaysia, followed by palm-oil mill effluent (38%), swine manure (6%), and industrial effluent (3%) [48, 49]. Based on previous research, it has been concluded that LFG relative amounts of 40-45% and 55-60% by volume, respectively, for biogas generation [50]. Biogas generally consists of 48-60% CH_4, 36-40% CO_2, and 17% N_2, <1% O_2, 32-169 ppm H_2S, and traces of gases [51]. A report evaluated total CH_4 emissions from waste in Malaysia as being 1.3×10 tons/year [3]. Total CH_4 was projected to be 2.2×10^3 tons/year in 1994 and 318.8×10^3 tons/year in 2009, and was expected to increase each year. Another study recorded an inventory on regional landfill CH_4 emissions in Malaysia [5]. The approximate values of CH_4 emissions from dumpsites and sanitary landfills were equal to 55.6% and 44.4%, respectively. For comparison, the literature on total CH_4 emitted from other Asian countries is presented in Table 6 [51-54]. The review provides the basis for the benefits arising from emission reduction, energy generation, and further research for landfill gas management.

Pulau Burung Sanitary Landfill has the maximum deposited MSW (19×10^3 tons) and methane reduction of 45,538 tons CO_2 equivalent. In addition, Bukit Tagar Landfill is the highest CH_4 capture facility (219,625 tons CO_2 equivalent) although it has a lower amount of waste capacity load (2.8×10^3 tons) in the landfill. Air Hitam Sanitary Landfill is the first grid in Malaysia linked as a renewable energy facility. The total gross area of the landfill is about 58 hectares, and the waste deposited is close to four million tons. The landfill areas receive 3,000 tons/day from major parts of the Klang Valley. It is owned by Jana Landfill and was constructed in 2003 to produce and utilize LFG for electricity using two Austrian-made internal combustion engines. The 2.096 MW power plants have a capacity of 1,048 kW, and the generator comprises a gas extraction system that is directly connected to the pipe from the gas field to well. The systems function as the fuel pre-treatment system of biogas such as filtration, heating, and cooling of the gas. The interconnection point of Tenaga

Table 5. Current landfill site availability in Malaysia.

Region	Number of sites		Disposal area (ha)		Total waste in millions of metric tons (mmt)	
	SLF	DS	SLF	DS	SLF	DS
Northern	3	43	52.1	599	22.8	33.7
Central	4	23	830.9	581.7	6.5	23.0
Southern	2	33	133.7	267.7	6.6	21.1
East Coast	1	62	28	650.7	2.9	15.5
Borneo	4	51	118.6	315.2	1.6	9.3
Total	14	212	1,163.3	2,414.3	40.4	102.6

SLF – Sanitary Landfill, DS – Dump Site

Table 6. Emissions of CH_4 from different countries.

Reference	Year	Country	Year of inventories	CH_4 emission (Gg)
[51]	2004	India	1980-1999	263.02-502.46
[52]	2007	Thailand	2005	120.6
[52]	2007	Thailand	2005	194.2
[53]	2007	China	2004	1,872-3,370.5
[54]	2009	Thailand	2007	89.22

Nasional Berhad (TNB) substation with the gas power generator is located 30 m from the site and two MW are transferred to the national grid. Each well can produce biogas for a period of 20 years and the gas composition is more than 55% CH_4 with an 80% maximum moisture level at a production rate of 40 m^3/h. Besides power generation, this project reduces odour levels in the surrounding area and mitigates emissions of GHG. Unavailingly, this facility was closed for operation since 2007 considering some mechanical and technical concerns.

Methane Generation in Landfill

Anaerobic Digestion in Landfill

Emission from landfill is commonly known as landfill gas (LFG) and accelerates greenhouse gas (GHG) formation due to a mismanaged landfill that resulted in environmental degradation. LFG basically consists of 50-55% of methane (CH_4), 40-45% of carbon dioxide (CO_2), and 1-2% of trace amounts of other gases. CH_4 generation in a landfill is produced in the absence of oxygen (O_2), called anaerobic digestion [55]. Anaerobic digestion is the process in which microorganisms break down organic constituents and is widely described as wastewater sludge, industrial, and farm waste because it provides volume and mass reduction of the input material. Anaerobic digestion is a biological treatment considered as an alternative energy resource due to the high amount of methane in biogas with energy value instead of utilizing fossil fuels. Besides this, sufficient nutrient solids and liquid discharge known as digestate also can be further stabilized and turned into a quality soil amendment. This is the alternative waste treatment from the destruction of organic content and diversions into valuable product. Most literature propose anaerobic digestion occurring in four separate phases: hydrolysis, acidogenesis (fermentation), acetogenisis, and methanogenesis as illustrated in Fig. 2 [56-64]. The degradation of organic matter into CH_4 is briefly explained as follows.

At the initial stage, the complex organic compound (carbohydrate, protein, and lipids) is hydrolyse by hydrolytic microorganism breaking down the long chain, producing carbon dioxide (CO_2), water (H_2O), and heat [65]. CH_4 production from anaerobic conditions depends on a microorganism consortia that works on degradation of high-complex organic molecules according to the stages involve in the process [66]. Some literature has explained that LFG generates from three processes that are bacterial decomposition, volatilization, and chemical reaction [67]:

Table 7. CH_4 estimation in Peninsular Malaysia by 2010.

State	MSW_T (tons/y)[a]	MSW_F	MC_F	DOC	DOC_F	F	16/12	CH_4 (tons/y)[b]
Kuala Lumpur	1,202,000	0.80	0.60	0.14	0.77	0.55	1.33	45,500
Selangor	1,595,000	0.80	0.60	0.14	0.77	0.55	1.33	60,370
Pahang	250,000	0.80	0.60	01.4	0.77	0.55	1.33	9,460
Kelantan	87,000	0.80	0.60	01.4	0.77	0.55	1.33	3,290
Terengganu	155,000	0.80	0.60	01.4	0.77	0.55	1.33	5,870
Negeri Sembilan	411,000	0.80	0.60	0.14	0.77	0.55	1.33	15,560
Melaka	310,000	0.80	0.60	0.14	0.77	0.55	1.33	11,730
Johor	1,395,000	0.80	0.60	0.14	0.77	0.55	1.33	52,800
Perlis	34,000	0.80	0.60	0.14	0.77	0.55	1.33	1,290
Kedah	941,000	0.80	0.60	0.14	0.77	0.55	1.33	35,620
Penang	833,000	0.80	0.60	0.14	0.77	0.55	1.33	31,530
Perak	983,000	0.80	0.60	0.14	0.77	0.55	1.33	37,210
Total	8,196,000	-	-	-	-	-	-	310,220

[a]The amount of CH_4 in LFG is 55%, hence F = 0.55

[b]From Equation 1

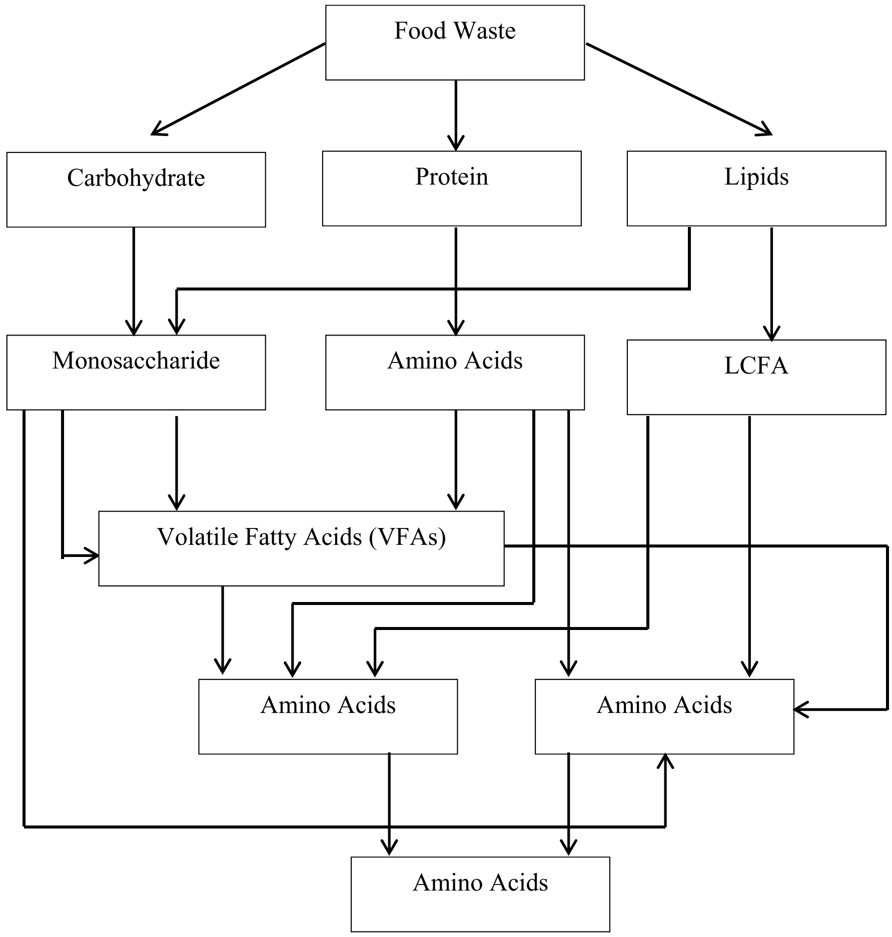

Fig. 2. General phases in anaerobic digestion.

Acetogenesis:

$$C_6H_{12}O_6 \longrightarrow 2C_2H_5OH + 2CO_2 \quad (1)$$

Glucose

Methanogenesis:

$$CH_3COOH \longrightarrow CH_4 + CO_2 \quad (2)$$

Acetic or ethanoic acid

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2 \quad (3)$$

Carbon dioxide and Hydrogen

The maximum amount of LFG generated in the anaerobic decomposition can be estimated by the following simplified reaction:

$$C_6H_{10}O_4 + 1.5H_2O \longrightarrow 3.2CH_4 + 2.75CO_2 \quad (4)$$

Adipic acid (waste)

Estimation of Methane Generation in Landfill

Estimations were done on the CH_4 generation from 296 landfills in Malaysia that recently reported using the Intergovernmental Panel on Climate Change (IPCC), 1996 methodology [5]. The IPCC model is based on the first-order decay. According to this model, CH_4 generation from landfill continues after some years, which begins to reach its maximum production in the first few years and gradually decreases. The anthropogenic CH_4 emission from anaerobic digestion of OFMSW using the IPCC equation is derived as follows:

$$CH_4 \text{ emissions (tons)} = MSW_T \times MSW_F \times MC_F \times DOC \times DOC_F \times F \times 16/12 \quad \text{(Eq. 1)}$$

...where MSW_T is the total MSW generated (tons), and MSW_F is the fraction of MSW disposed of in a landfill and measured as 0.8 as 80% of the total MSW disposed in landfill [68]. The default value for MC_F is 0.6 for CH_4 correction factor [69], while the default value for DOC is 0.14 as the fraction of degradable organic carbon [70]. The DOC_F is taken as 0.77, showing the fraction of total DOC that actually degraded [71]. The amount of CH_4 in LFG is taken as 55%, hence F=0.55 (F described CH_4 fraction in LFG). It is predicted that there is no activity for methane harnessing and so R is zero while the oxidation factor is also zero.

The estimation of CH_4 in Peninsular Malaysia by 2010 substituting the value from Table 1 into Equation 1 is presented in Table 7. The study found that landfills in Malaysia emitted almost 310,220 tons/year of CH_4 in 2010 with MSW_T = 8,196,000 tons/year. This was compared to emissions from other Asian countries as summarized in Table 4. According to Table 4, the accumulation of CH_4 distribution

Table 8. Sanitary landfill characteristics in Malaysia.

Facility	State	Condition	Waste in place (2009) (10^3 t)	Current CH_4 status	Year CH_4 reduction started	Average CH_4 emission reduction (t CO_{2eq})
Pulai	Kedah	In operation	440	No recovery	-	-
Ampang Jajar	Pinang	Closed	3,360	No recovery	-	-
Pulai Burung	Pinang	In operation	19,050	Passive aeration	2010	45,538
Johor Jerangau	Pahang	In operation	2,930	Recovering	2008	15,418
Air Hitam	Selangor	Closed	1,610	No recovery	-	-
Kg. Hang Tuah	Selangor	Closed	530	No recovery	-	-
Jeram	Selangor	In operation	1,500	No recovery	-	-
Bukit Tagar	Kuala Lumpur	In operation	2,850	Recovering	2009	219,625
Krubong	Melaka	Closed	4,100	Recovering	2007	57,830
Seelong	Johor	In operation	2,500	Recovering	2007	108,335
Meradong	Sarawak	In operation	40	No recovery	-	-
Sibuti	Sarawak	In operation	300	No recovery	-	-
Kuching	Sarawak	In operation	820	Recovering	2009	48,507
Kemunyang	Sarawak	In operation	410	No recovery	-	-

in Malaysia was greater compared to Thailand, whereas India and China are used as comparative countries because they have higher populations, hence higher emissions. From the total CH_4 estimated emission, 55.6% is contributed from dump sites, and the remainder is expected from sanitary landfills (44.4%). The average CH_4 emission considers the number of sites, and the resulting emissions from sanitary landfills are higher than dump site emissions. In general, OFMSW degradation under anaerobic conditions in sanitary landfills promotes the higher contribution of average CH_4 than dump sites due to soil cover presence on top of the barrier cover, enhancing the volume of CH_4 formation.

Nevertheless, intrusion of air into dumped sites because of insufficient cover materials offers oxygen that inhibits CH_4 production. Landfills in Selangor and Kuala Lumpur generated the highest CH_4 in 2010 – approximately 63,700 tons and 45,500 tons, respectively, which is directly in proportion to the waste generation. The correspondent electricity principle in 2010 was approximately 310,220 tons/year, which is predicted to be about 1.5% of the total Malaysian energy requirement. This figure is foreseen to increase to 350,000 tons/year and 370,000 tons/year in 2015 and 2020 [72]. These numbers clearly point to this type of resource slowly replacing fossil fuels in the future as the main source of energy.

The layout of some Small Renewable Energy Project (SREP) of LFG types in 2004 was approved by the government to encourage the implementation of renewable energy. It was proposed to the Nations Framework Convention on Climate Change (NFCCC) as Clean Development Mechanism (CDM) projects. LFG energy facilities will capture natural gas, mainly containing CH_4 and for energy resources [73]. Table 8 compares existing sanitary landfills and methane captures activities as reviewed [22]. Currently, the total energy generated under SREP is 241.65 MW, and only 43.5 MW is connected to the system grid as presented in Table 9. By approximately 2015 the projected energy recovery from renewable sources such as biomass and biogas are 330 MW and 100 MW, respectively [34].

Potential of Energy Recovery from MSW in Malaysia

The potential energy generation in California was estimated according to Matteson and Jenkins and is used in this review to approximate energy recovery through anaerobic digestion of OFMSW in Malaysia [74]. The same study also was done to estimate power generation from food waste in Taiwan [75]. The expression is derived as in Equation 2, and is suitable to overview potential energy generation for a large area and considers only CH_4 generation, as CH_4 is the majority contained gas (50-70%) and most useful component in biogas.

$$CH_4 = q \times f_{vs} \times b \times g \times C_{CH_4} \tag{Eq. 2}$$

...where CH_4 is the total of CH_4 generated (dam^3); q is the available amount of MSW (Mg); f_{vs} is the ratio of volatile solids to total solids (unit less); b is the volatile solids biodegradability for food waste (unit less); g is the biogas yield (dam^3 Mg/VS destroyed); C_{CH_4} is the concentration in biogas ($m^3 \cdot m^{-3}$).

The power potential generation can be calculated based on the Equation 3 derived from Equation 2:

Table 9. Total export capacity of renewable energy in Malaysia.

Fuel type	Company	Export capacity (MW)
Biomass (EFB & MSW)	TSB Bioenergy	10
	Kina Biopower	10
	Seguntor Energy	10
	Recycle Energy	6
Biogas	Jana Landfill	2
Mini hydro	Esajadi Power	2
	AMDB Berhad	4

Table 10. Estimated values for parameters derived for Equations 2-4 from literature.

Parameter	Value	Reference
f_{vs}	0.84	[26, 68, 69]
b	0.83	[76-80]
g	0.55	[26]
C_{CH_4}	0.71	[26, 77-79]
η	34%	[26, 77-79]
Q_{CH_4}	36.3 MJ·m^{-3}	[74, 75, 80]

$$E_{AD} = \frac{1}{3600} \times q \times f_{vs} \times b \times g \times C_{CH_4} \times Q_{CH_4} \times \eta_e \quad \text{(Eq. 3)}$$

...where E_{AD} is the potential for electric recovery (MWe/year), (1/3600) is the conversion factor for kWs to kWh, QCH_4 is the heating value CH_4 (MJ·m^{-3}), and η_e efficiency assumed for the conversion of CH_4 to electricity (unitless).

Heat generation potential from conversion of LFG can be estimated using Equation 4, which is derived from Equations 2 and 3.

$$H_{AD} = \frac{1}{1000} \times q \times f_{vs} \times b \times g \times C_{CH_4} \times Q_{CH_4} \quad \text{(Eq. 4)}$$

...where H_{AD} is the heating potential (TJ/year).

The estimated values for parameters derived from Equations 2-4 from collective literatures are described as in Table 10. Utilizing the Matteson and Jenkins [74] estimation, Malaysia potentially generates 1.26×10^6 dam^3 of CH_4, which is projected to equal 4,308 MWe/year of electricity and 46 PJ/year of heat production by the year 2020.

Malaysian energy consumption in 2003 is 373 TW/year and expected to grow at 5.4% per annum and reach 917 TWh in 2020 as presented in Table 11. The increment is due to industrialization in manufacturing and transportation sectors. However, 100% conversion of OFMSW from anaerobic digestion offers about 4.3 TW/year or 1.15% of Malaysian electricity demand by 2020. Waste separation at source is crucial in order to achieve the benefits mentioned above. Any impurities that are generally found in OFMSW should be removed to ensure the efficiency of the operation process. Table 12 is the summarized breakdown of food waste for each state. The values presented in the Table 12 are based on the theoretical measurement that offers economic and environmental benefits. A farther advancement of mathematical modelling is crucial for optimization of the digestion operation.

Sustainability in Environmental, Energy, and Economic Aspects

Environmental Benefits

The accumulation of OFMSW in landfill has become a major environmental and health concern. Leachate and landfill gas (LFG) intrusion into the environment leads to water and air pollution. LFG-contained methane (CH_4) is a potential resource, unfortunately allowing it into the atmosphere and introducing the biggest environmental concern. CH_4 contributes by depleting the ozone layer as CH_4, which has 21 times the global warming potential of carbon dioxide (CO_2). LFG harnessing and waste diversion to promote biogas production ensures mitigation of emissions. By implementing LFG, projects may minimize the subsurface migration from landfill and reduce fire and explosion hazards [24, 25]. In fact, the energy generated from biogas is clean, which will curb the impact of using fossil fuels for transportation and to operate mechanises. The critical issue facing the fossil-fuel power generation sector in Malaysia is the over dependence on natural gas and coal as the main

Table 11. OFMSW potential energy recovery based on Matteson and Jenkins [74] estimation.

Energy recovery	2010	2015	2020
Total MSW generation (tons)	8,196,000	9,111,000	9,820,000
Food waste estimated (tons)	3,852,120	4,282,170	4,615,400
Potential CH_4 generation (dam^3)	1,048,765	1,165,849	1,256,573
Potential power generation (MW_e/year)	3,595	3,997	4,308
Potential heat generation (TJ/year)	38,070	42,320	45,613
(PJ/year)	38	42	46

Table 12. Breakdown of annual potential energy for each state in Malaysia by 2020.

State	TMSW (tons)	Estimated food waste (Tons)	Potential CH_4 generation (dam^3)	Potential power generation (MW_e/year)	Potential heat generation (PJ/year)
Kuala Lumpur	1,322,000	621,340	169,164	580	6,14
Selangor	1,950,000	916,500	549,523	855	9,058
Pahang	290	136,300	37,109	127	1,347
Kelantan	42	19,740	5,374	18	195
Terengganu	185	86,950	23,672	81	860
Negeri Sembilan	531	249,570	67,947	233	2,466
Melaka	395	185,650	50,544	173	1,835
Johor	1,785,000	838,950	228,409	783	8,291
Perlis	30	14,100	3,839	13	140
Kedah	1,251,000	587,970	160,079	550	5,811
Penang	1,018,000	478,460	130,264	447	4,729
Perak	1,021,000	479,870	130,648	448	4,743
Total	9,820,000	4,615,400	1,256,573	4,308	45,615

resources. However, the government through 9th and 10th Malaysia Plans is formulating an action plan to improve energy efficiency to reduce the impact of the energy sector on the environment and conservation of fossil fuels. From the Energy Efficient Program in Malaysia, savings of 1,400 GWh are estimated, worth RM 238 million during the implementation of the plan. The average cost of energy saved will be RM 0.11/kWh.

Energy Future Outlook

The Malaysian energy sector still depends on natural sources of fuel such as fossil fuel and natural gas. Researchers are intensively searching for new emerging alternative energy due to energy security and the environment. Anaerobic digestion of OFMSW for biogas production has become a worldwide focus of research, because it produces energy that is green, and a renewable energy resource instead of reducing dependency on fossil fuels. The bioconversion process from anaerobic digestion can be an alternative solution prior to sustainable landfill management and produce biogas for energy and heat utilization [81]. In order to find alternatives for future energy resources, it is also important to look into potential and energy efficiency. CH_4 generation in landfills can cause direct pollution to the atmosphere. Dumping of organic waste, especially food waste, in landfills is an unsustainable waste management practice, as the materials still represents a valuable nutrient source and energy value. Sustainability and stability of energy supply does not really depend on the amount of the sufficient energy supply [82]. The formation of biogas through anaerobic digestion is a clean and green fuel, even though it comprises only 50-65% of CH_4. In most applications it is possible to introduce it in power gas engines. However, purification and upgrading the biogas is necessary for latter application, which obviously added value to the biogas [83].

The current global interest in renewable energy and biofuel production, especially in the area of transportation fuels, presents the opportunity to generate electricity from organic waste as well as increased export earning in Malaysia. Moreover, CH_4 from MSW is a "free" source of energy compared to conventional energy sources instead of ensuring energy security and the environment.

Economic Perspectives

LFG gas is most known as the cause of direct pollution to the atmosphere, but harvesting LFG promotes a significant reduction in the need for fossil fuels and foremost is pollution reduction. Previous studies have reported that LFG contains almost 55% methane with the calorific value of 17 MJ/m^3 [53]. Table 13 describes energy potential from methane harvesting. The main usage of methane from landfill is basically for energy resources instead of contributing environmental and economic benefits. By applying a GWP of 21 and US$13.20/ton CO_2, the equivalent CO_2 reduction and revenue from carbon credit and with a CO_2 emission reduction of 6.51 Mt CO_{2eq} for 2010, the deduction is progressing to be 7.24 and 7.81 Mt CO_{2eq} by 2015 and 2020, respectively. Equivalent CO_2 reduction was estimated by multiplying annual methane emissions by 21, as methane has about 21 times the global warming potential of CO_2. The value of reduction equivalent in 2010, for instance, is 6.51 MtCO_{2eq}, which is over 13% of total carbon emissions in Malaysia [84]. The implementation of the Clean Development Mechanism (CDM) project or any other

Table 13. Biogas energy efficiency from OFMSW.

Energy efficiency	2010	2015	2020
CH_4 emission (tons/year)	310,225	344,858	371,696
60% CH_4 (tons/year)	186,135	206,914.8	223,017.6
Equivalent CO_2 emission ($MtCO_{2eq}$)[a]	6.51	7.24	7.81
Revenue from carbon credit[b]	US$85.93 RM 257.79[c]	US$95.57 RM 286.71[c]	US$103.09 RM 309.27[c]
Equivalent electricity generation ($\times 10^9$ kWh/year)	2.2	2.4	2.6
Revenue from electricity ($\times 10^6$)[d]	RM 660 US$220	RM 720 US$240	RM780 US$260

[a] Based on GWP, CH_4 is 21 more hazardous than CO_2, [b] Based on US$ 13.2/tons of CO_2, [c] Based on US$ 1 = RM 3.00, [d] Based on US$ 0.1/kW h, RM – Ringgit Malaysia (Malaysian currency)

renewable energy scheme on CH_4 capture, in 2010 (based on US$13.20/tons) the carbon reduction could gain revenue of RM 257.790 million (US$85.930 million), RM 286.710 million (US$9.570 million), and RM 309.270 (US$103.090 million) estimated for 2015 and 2020, respectively. In addition, equivalent electricity generation of 2.2, 2.4, and 2.6×10^9 kWh is achievable in 2010, 2015, and 2020, respectively.

The estimated equivalent electricity generation in 2010 of 1.9×10^9 kWh is about 1.5% of the total electricity consumption in Malaysia or equivalent to electricity needs for 420,000 Malaysian citizens [85]. Furthermore, based on RM0.30/kWh the electricity generated could be sold to attract revenue up to RM 570 million (US$190 million), RM660 million (US$220 million), and RM690 million (US$230 million) in 2010, 2015, and 2020, respectively [86]. In the same mechanism, the global warming mitigation potential of a family-sized biogas plant was 9.7 tons CO_{2eq}/year with the current price of RM30 (US$10) per ton carbon equivalent with earnings from carbon credit per year of RM291 (US$97) [87].

Carbon dioxide contributes by volume a significant percentage of LFG. If the gas is allowed to pass through a filtering process, it could be recovered at minimal cost and made available to carbon dioxide users. LFG energy projects will lead to the creation of jobs that are associated with the design, construction, and operation of an energy recovery system. Electricity generation cost depends on investment cost and variable cost, which include capital cost, operational, maintenance, and fuel costs. Additional factors affecting the cost of biomass-based power generation include power capacity, power plant life-times, heat and electricity efficiency, and load factor of power plan [88]. To overcome the limitations of biogas-based power generation cost, developers must take a long-term view and continue to exploit emerging technologies that can reduce the electricity generation cost from renewable resources. Energy efficiency varies depending on technology used for the conversion process. This area always gives much attraction to achieve efficient energy conversion [89].

Challenges and Future Prospects

The Malaysian government through the Solid Waste and Public Cleansing Management (SWPCM) Act in 2007 encourages the development of nationwide modern and sustainable sanitary landfill operations with methane gas capture facilities. There are several advantages and opportunities in harnessing biogas in landfills, but there are also challenges and limitations need to be addressed. The biogas sector in Malaysia is relatively new, and utilizing biogas as an energy resource is still in the research and monitoring phase. Hence the government should support methane gas harnessing through an empowerment energy policy, plus design and construction of the digester operation. Most important is support for maintenance.

Even though biogas sectors are able to mitigate some environmental problems and resolve energy resource shortages, the technology requires high capital investment [90]. However, regarding the financial capability, Malaysia is bestowed with a significant amount of MSW generation by diverting the waste as the resources to generate potential renewable energy. Perhaps there is now a foundation as a supporting measure to encourage renewable energy implementation in Malaysia such as electricity feed-in tariff from 17 cents/kWh up to 21 cents/kWh for biogas and biomass.

Other obstacles, such as environmental conditions and the equipment as system set-up for a biogas harvesting operation, may not be applicable to a tropical country like Malaysia. The system installed may be inoperable due to deterioration from humid weather and climate change [91]. Hence developers need to consider the material for pipeline and gas pump as the main parts to channel the gas for storage. In fact, local expertise can be sufficient to supervise and conduct the performance of a gas capture operation. In order to establish and promote the biogas sector, the government should develop a support system through training and educating personnel from other countries that already have established their biogas system operation, such as Germany, China, and South Korea. In Malaysia local authorities are committed to developing biogas because of its opportunity in marketing, and there are also study groups focusing on biogas developments in universities in Malaysia. Public perspective and information on biogas are limited. Knowledge about this technology and awareness of the environment and the forthcoming energy catastrophe have to be publicized in order to grasp the perspective of Malaysia's oncoming energy endeavors.

Conclusions

MSW in Malaysia contains high putrescible waste such as OFMSW, mainly contained in perishable food waste that is commonly disposed of in a landfill. Harvesting methane (CH_4) from anaerobic digestion of OFMSW either from landfill gas (LFG) or anaerobic treatment facilities could potentially promote energy recovery and mass reduction. On the other hand, Malaysia is pressing to alternate and expand renewable energy by obtaining all inclusive potential energy resources. Landfill gas, mainly CH_4, has been shown to offer excellent renewable energy resources known as biogas. This will reduce over-dependence on non-renewable fossil fuels with their attendant unstable price and occasional supply interruptions. Landfill gas recovery through the capturing and utilization for power generation, fuel, or as feedstock will cater a considerably uppermost mechanism to reduce overall greenhouse gas transmissions from landfills. The CH_4 compressed in the mix of landfill gas will be utilized to generate electricity or instantaneously replace fossil fuels such as oil and coal, which is more environmentally friendly. This is also a betterment for the implementation of the substitute fuels program, for example carbon credits through the Clean Development Mechanism (CDM,) which also give the added benefit of extending the life of a landfill through volume reduction in the form of energy.

This review critically focuses on diverting OFMSW from landfill to offer energy and mass recovery, pollution, and contamination mitigation. The review shows that there are immense opportunities and advances in bioconversion on organic materials in MSW landfill to generate electricity. Anaerobic digestion of OFMSW in Malaysia, as projected by 2020, could potentially generate renewable energy resources for Malaysia, but needs to take fast action to manage degradable material in a sustainable manner in order to prevent environmental problems. The main stakeholders such as government, institution, and society should encourage the implementation of anaerobic digestion as the best practicable solutions toward organic waste accumulations.

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