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Biogas and biofertilizer production from organic fraction municipal solid waste for sustainable circular economy and environmental protection in Malaysia

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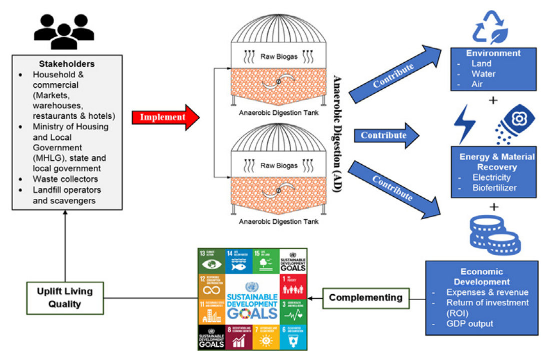
HIGHLIGHTS

- The potential of resource recovery form organic waste for a circular economy and in Malaysia was investigated.
- Anaerobic digestion of OFMSW can result in 3941 MWh/day of electrical and 2500 Mg/day of biofertilizer.
- A total of 2735 Mg/day of CO_2 emission, 1128 m^2/day of landfilling area and 481 m^3/day of leachate can be avoided.
- Economic development can go hand-in-hand with environmental sound practices in the field of waste management.

GRAPHICAL ABSTRACT



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ABSTRACT

Waste management in Malaysia remains a persistent economic and environmental challenge. Up to date, more than 80% of Malaysian solid waste disposed at landfills and dumpsites. Therefore, Malaysia is facing an urgent need to move towards a sustainable solid waste management and thus resource recovery from organic solid waste. Hence, this study aims to investigate the feasibility of energy and bio fertilizer recovery from organic fraction municipal solid waste (OFMSW) via anaerobic digestion. The economic and environmental benefit analysis was investigated. Approximate and elementary analysis of OFMSW samples were carried out to estimate the potential production of biogas and bio fertilizer. It was found that organic waste contributes about 45% of the total MSW generated in Malaysia. Anaerobic digestion of 50% of organic waste is expected to produce 3941 MWh/day of electrical energy and 2500 t/day of bio fertilizer. In terms of environmental impacts, 2735 t/day of Carbon dioxide (CO_2) emission, 1128 m^2/day of landfilling area and 481 m^3/day of leachate can be avoided. A net revenue of 3300 million RM (1 US Dollar ≈ 4.15 RM) can be generated by the sales of electricity via Feed-in-Tariff (FiT), sales of biofertilizer to local agricultural industries and inclusive of the saving generated from the reduction of OFMSW landfilling operations and leachate treatment at landfills. Economic development can go hand-in-hand with environmental sound practices in the field of waste management.

1. Introduction

Humanity and global economic activities are being so profound and prevalent in many ways had altered, breached and outcompeting natural threshold, processes, and systems by inducing persistent human-driven crisis at a global level namely global warming, land-use changes, lost in biodiversity, ocean acidification, desertification and altered in global Nitrogen and phosphorus flow (Rockström et al., 2009). This era of human dominance on Earth is known as "Anthropocene" or in simple terms "The Earth as Modified by Human Action" (Crutzen, 2006) as there are now 7.7 billion people which is roughly 9–10 times the 800 million people

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Nomenclature

AD	anaerobic digestion
CAPEX	capital expenditure
FiT	Feed-in-Tariff
GDP	gross domestic product
GHGs	greenhouse gases
MSW	municipal solid waste
OFMSW	organic fraction municipal solid waste
OPEX	operational expenditure
ROI	return of investment
POME	palm oil mill effluent
SWM	solid waste management
UN-SDGs	United Nations Sustainable Development Goals

estimated to have lived in 1750 (Worldometers, 2019). Burgeoning population, continuous economic development and higher quality of living had led to the unavoidable continuous rise in energy and material demand and consumption. This leads to the increase in waste generation, Carbon emissions, electricity consumption and environmental degradation. According to Kaza et al. (2018), 69.7% of global waste generated is either landfilled or open-dumped. Landfills contributes to various environmental issues for instance, the release of the 25-fold in global warming potential Methane gas, CH_4 in comparative to Carbon Dioxide gas, CO_2 resulted from the decomposition of organic or biodegradable waste fraction (Brander and Davis, 2012). The released landfill leachate pollutes surrounding water, soil resources and ecological system (Abuabdou et al., 2020) as leachate often contain concentrated pathogenic organic matter, bacteria, hazardous heavy-metals, and other refractory and carcinogenic compounds (Yong et al., 2018). By 2050, global waste is expected to grow as the waste generation per capita per day is projected to increase by 19% in high-income countries; 40% or more in low- and middle-income countries (Kaza et al., 2018).

About 49,670 t/day of MSW was collected in Malaysia (MHLG, 2015). Food, kitchen, and organic waste in Malaysia contributes the largest portion (45%) of total MSW followed by plastics (13%), diapers (12%), paper (9%), and garden waste (6%). Therefore, a grand total of 27,319 t/day of OFMSW generated in year 2020. These wastes are currently disposed into landfills. Landfills and solid waste sectors contribute 11% of global anthropogenic greenhouse gases (GHGs) due to the continuous release of CH_4 due to the decomposition of OFMSW that are being cast off in landfills (Yritys, 2018). Furthermore, the consumption and generation of electricity from 85.99% of fossil fuel as global primary energy source had leads to an annual 3.95% increase in global CO_2 emissions (World Energy Council, 2016). Since solid waste is a transboundary sector which affects sanitations, urban living quality, public health, natural ecosystem, jobs and use of resources; therefore, solving solid waste management (SWM) issues can contribute to more than 50% of high-level United Nations Sustainable Development Goals (UN-SDGs) (Rodić and Wilson, 2017). Therefore, the anaerobic digestion (AD) process is the most environmental and economical preferable and proven solution in the treatment and recovering of energy and resources from all types of organic waste (Moustakas and Loizidou, 2019).

Malaysia had an average annual increase of 5.19% in solid waste generation since 2015 of 3856 t/day to 4967 t/day in 2020 (MHLG, 2015). Unfortunately, more than 80% of Malaysian waste are being landfilled and open dumped into all 297 landfills with only 10 are sanitary compliance with minimal environmental hazards control (MHLG, 2015). Moreover, the recycling rate in Malaysia is very minimal at 5–10% even though 70–80% of the MSW are recyclable (Johari et al., 2014). This contributes to an annual increase of 3.59% of CO_2 emission/capita in Malaysia resulting from the degradation of organic waste in landfill releases GHGs (The World Bank, 2019). Another factor which causes the increase in CO_2 emission is the 8.12% annual increase in electricity consumption in Malaysia to 12,517 kilo-tonne-oil-equivalent (ktoe) in 2017 from 766 ktoe in 2007 where 92% of electricity is generated from fossil fuel resources (Energy Commission Malaysia, 2019). In terms of economics, at least half of the annual state expenditure in Malaysia are spent on managing municipal solid waste and public cleansing while the capital expenditure (CAPEX) and operating expenditure (OPEX) for establishing a new landfill is RM30 million and RM30.0–40.0/t/day respectively (Zainu and Songip, 2017). According to Rohatgi (2017), in Malaysia the Feed-in-Tariff (FiT) mechanism of installed renewable energy capacity is 460 MW which is far lower than neighboring countries such as Thailand (6766 MW), The Philippines (4552 MW), Indonesia (3883 MW) and Vietnam (2569 MW).

Organic fraction municipal solid waste (OFMSW) is one of many anthropogenic biomass residues which is widely available. Through various thermo-chemical and bio-chemical conversion pathways, several alternative energies (biogas, electricity, and heat) and material products (renewable diesel, fertilizer, bio-oil) can be derived from wastes and biomass residues which currently are at various stages of economic and technical maturity (Salah et al., 2021; Liu and Rajagopal, 2019).

The most suitable and sustainable way to treat OFMSW which contains high in moisture is through anaerobic digestion (AD). This is because anaerobic digestion can effectively decompose a wide range of organic wastes (Isa et al., 2020) in a controlled environment to produce CH_4 rich biogas and nutrient rich compost (Brincat, 2015). Urban circular economy can be achieved through AD of OFMSW in Malaysia to generate renewable electricity from biogas and bio fertilizer in Malaysia. This process can significantly minimize various environmental pollution by avoiding direct waste disposal into the environment (Isa et al., 2020) furthermore maximizes renewables and therefore generating revenue from the products of AD (Yong et al., 2020).

At present, AD is the most applicable, promising, and proven biological conversion pathway which the technology itself had already reached technical and economic maturity in recovering industrial organic waste into electricity, heat, and fertilizer (Tyagi et al., 2018). In Malaysia, AD has been widely used in commercial palm oil mill industries where palm oil mill effluent (POME) is converted into biogas by anaerobic process (Abuabdou et al., 2020). Therefore, AD can be implemented nationwide to effectively convert OFMSW into renewable electricity and biofertilizer to minimize and avoid OFMSW to be harmful to the environment. Moreover, waste-to-energy is in-line with the present Malaysian governmental policy by the usage of OFMSW as a renewable feedstock for biogas-to-electricity generation, will directly complement to the pledge of the Malaysian government in Pledge No. 39: Balancing economic development with natural environmental protection and conservation (Pakatan Harapan, 2015).

As shown in Fig. 1, The separate collection and processing of organic via anaerobic digestion instead of landfills to generate renewable energy and organic fertilizer will contribute to environmental protection, renewable energy production and economic growth. Concurrently, the mentioned benefits can support the complements of 10 SDGs including No. 1-No Poverty, No. 3-Good Health & Well-Being, No. 6-Clean Water & Sanitation, No. 7-Affordable & Clean Energy, No. 8-Decent work & Economic Growth, No. 11-Sustainable Cities & Communities, No. 12-Responsible Consumption & production, No. 13-Climate Action, No. 14-Life Below Water and No. 15-Life On Land (Yong et al., 2020). This will bring positive impact in terms of upgrading living quality to all the stakeholders and entirely the Malaysian society.

In the light of the above mentioned, this study provides a scientific analysis on the potential bioenergy, biofertilizer and total environmental impact by converting OFMSW into renewable electricity and biofertilizer via AD. In addition, this study considered land-use saving, leachate and gas emission avoidance which are normally overlooked by the literature. Economic feasibility analysis was conducted to calculate the return of investment (ROI) of such project if being applied in Malaysia. Finally, the sustainable development goals (SDGs) analysis was conducted to value the contribution of such project in the context of Malaysia by relating each environment, energy, and economic

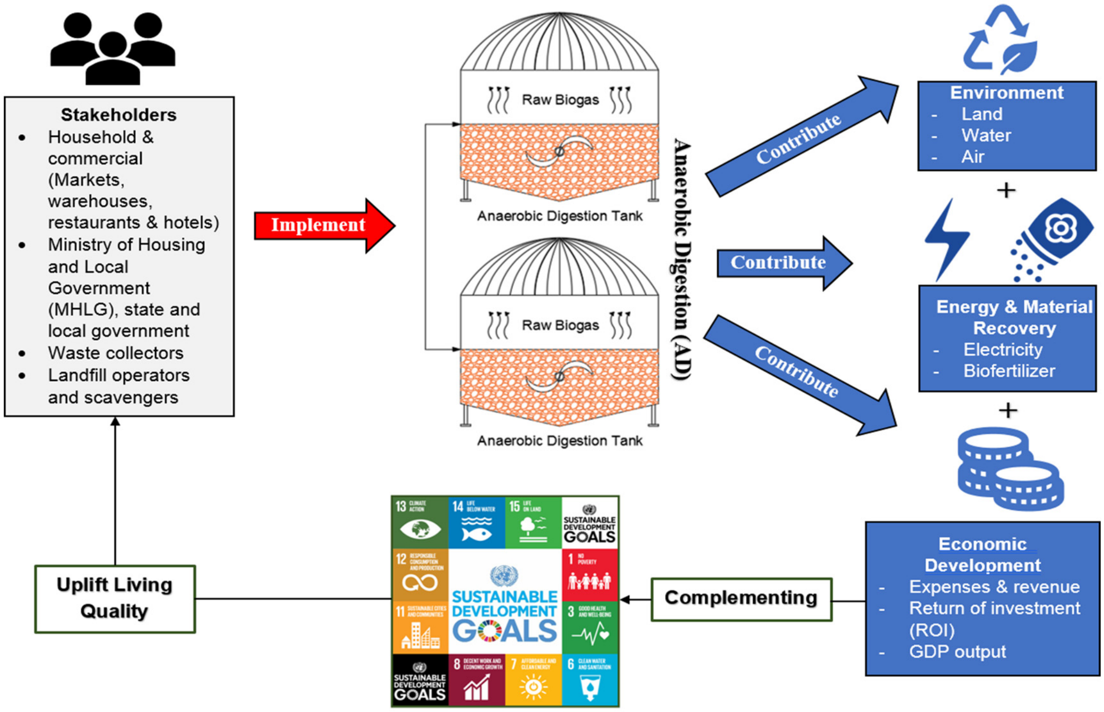

Fig. 1. Conceptual framework of applying anaerobic digestion for recovering electricity and fertilizer from organic municipal solid waste (OFMSW) in Malaysia.

outcome with specific goals. Through the analysis of the SDGs relating to the implementation of AD of OFMSW and its various benefits, Malaysia can be a role model for other neighboring countries towards the sustainable management of OFMSW.

2. Materials and methods

2.1. Organic fraction municipal solid waste (OFMSW) sampling

The OFMSW samples were sourced at Sahom Landfill at Jeram, Kampar, Malaysia at Coordinate (4.392594, 101.179842). Fig. 2 illustrates the procedures followed from sourcing OFMSW directly from fresh arrival household mixed waste at the landfill to sample preparation at laboratory. The OFMSW was directly segregated from household mix waste and is transferred into a large green roller bin where the bin also contains collected food and kitchen wastes from residential and commercial areas. Then, the OFMSW was taken out and distributed on the floor in a composting center just next to the landfill. This was followed by the mixing of OFMSW samples to remove any unwanted large inorganic and hard contaminants. After the OFMSW has been mixed homogeneously, the samples were collected in a cleaned container and directly placed into the laboratory refrigerator.

2.2. Sample preparation and homogenization

Fig. 2 shows the standard protocol to homogenize and prepare the OFMSW samples according to Esteves and Devlin (2010). The freshly

Fig. 2. Procedure of sampling to preparation of OFMSW.

collected OFMSW sample was first stored in laboratory refrigerator at 4 °C for 24 h for the first stage homogenization. Then, the sample was heated to room temperature by water bathed. Large contaminants were removed (bones, strings, plastics, metals, and other inorganics) before chopping sample into smaller pieces and mixing using kitchen knife for the second stage homogenization. An empty 250 mL beaker was weight and recorded. The chopped sample was transferred into the 250 mL beaker for weighing and the actual sample weight was recorded. 100 mL–150 mL of distilled water was measured. The distilled water was then transferred together with the samples into the laboratory blender. The purpose of adding distilled water was to enable sufficient liquid present in the blender to create vortex and hence good mixing in the vessel. The third stage homogenization involves the blending and shredding of sample using the laboratory blender. The blended sample was then transferred into sampling bottle for analysis or storage.

2.3. Characterization and properties of sample

Physical and chemical characterizations of OFMSW samples were carried out including approximate and ultimate analysis as shown in Table 1. Ultimate analysis was conducted to measure carbon, hydrogen, nitrogen, sulphur, and oxygen elemental weight percentage, %.

3. Theoretical calculation and estimations

3.1. Biogas composition

The percentage of the biogas composition (CH_4 to CO_2) was determined by equation, Eqs. (1) and (2) (Banks, 2009) modified from Buswell and Mueller (1952) formula:

Buswell general equation:

$$CH_4 = \frac{1}{8}(4C + H - 2O - 3N - 2S) \quad (1)$$

$$CO_2 = \frac{1}{8}(4C - H + 2O + 3N + 2S) \quad (2)$$

where, CH_4 = ratio of methane gas; CO_2 = ratio of carbon dioxide gas; C = % weight of carbon; H = % weight of hydrogen; O = % weight of oxygen; N = % weight of nitrogen; S = % weight of sulphur.

3.2. Volume of biogas and CH_4 gas generation

The volume of pure CH_4 yield, V_{CH4} was calculated by Eq. (3) (Banks, 2009; Ngumah et al., 2013), while the total volume of biogas is calculated by dividing the V_{CH4} over the CH_4 ratio calculated using Eq. (1):

$$V_{CH4} = \left[(C \times CH_4 \div M_{carbon} \times STP) \times \left(\frac{VS}{100} \times 0.75 \times M_{organic}\right)\right] \quad (3)$$

where, V_{CH4} = volume of pure CH_4 yield, m^3/day; C = constant of 75% VS degrades for biogas production, 0.375 gC/gVS; CH_4 obtained from Buswell and Mueller formula, %/100; M_{carbon} = molecular weight of carbon, 12 g/mol; V_{STP} = volume of 1 mol gas at standard condition, 22.4 L; VS = volatile solid percentage of organic MSW, %; $M_{organic}$ = Incoming mass of organic MSW stream, kg/day; Biogas = volume of biogas yield, m^3/day.

3.3. Bioenergy and biofertilizer potential

The electrical energy output from the biogas system was determined by Eqs. (4) (Banks, 2009) and (5) (Surroop and Mohee, 2012) respectively:

$$E_{bio} = V_{CH4} \times E \times \frac{Nel}{100} \quad (4)$$

where, E_{bio} = electrical energy output, kWh/day; V_{CH4} = volume of pure CH_4 yield, m^3/day; E = energy constant of CH_4, 10 kWh/m^3; N_{el} = electrical efficiency of biogas engine, 40%.

$$P_{bio} = \left(M_{organic} \times Y \times \frac{D}{100} \times P \times LHV \times C \times \frac{Nel}{100}\right) \times 1000 \quad (5)$$

where, P_{bio} = electrical power output, kW; $M_{organic}$ = mass of organic waste inflow, kg/h; Y = biogas yield, m^3/kg; D = CH_4 fraction in percentage, %; P = CH_4 density, 0.717 kg/m^3 at STP; LHV = lower heating value of CH_4, 50 MJ/kg; C = conversion constant from MJ/h to kW, 0.2778; N_{el} = electrical efficiency of biogas engine in percentage, %; E_{bio} = electrical energy output, kWh/day.

The electrical energy, E_{bio} in Eq. (4) was calculated by dividing the power, P_{bio} obtained in Eq. (5) by 24 h. The generation of bio fertilizer from digested OFMSW was determined by applying Eq. (6) (Ngumah et al., 2013). According to Deublein and Steinhauser (2011), biogas

Table 1
List of characterization of OFMSW.

Properties	Unit	Characterization methods	Equipment used (model)
Physical properties			
Temperature	°C	Thermometer probe	pH/ORP Multimeter (Hanna HI2550, Romania)
pH	–	pH sensor	pH/ORP Multimeter (Hanna HI2550, Romania)
Oxidation-reduction potential	mV	ORP probe	pH/ORP Multimeter (Hanna HI2550, Romania)
Dry mass	%	APHA, 1998	Laboratory Oven (memmert UF 110, Germany)
Moisture content (MC)-Wet sample basis	%	APHA, 1998, method 2540B	Laboratory Oven (memmert UF 110, Germany)
Total solids (TS)-Wet sample basis	%	Sample dried at 105 ± 2 °C (APHA, 1998, method 2540B)	Laboratory Oven (memmert UF 110, Germany)
Volatile solids (VS)-Dry sample basis	%	Sample ashed at 550 ± 25 °C (APHA, 1998, method 2540E)	Muffle Furnace (LabTech LEF-112P-1, France)
Chemical properties			
Calorific value	kJ/g	Bomb calorie method (ASTM D2015-00)	Boom Calorificmeter (IKA C200, China)
Ammoniacal-nitrogen (NH_3-N)	mg/L	Nessler Method (APHA, 2005) USEPA Nessler Method 8038 (Hach, 2019)	Nessler Reagent (Hach); Spectrophotometer (Hach DR 6000, USA)
Chemical oxygen demand (COD)	mg/L	USEPA Reactor Digestion Method 8000 (Hach, 2019)	COD Heat Reactor (Hanna HI 839800, Italy); Spectrophotometer (Hach DR 6000, USA)
Total organic carbon (TOC)	mg/L	EPA (Method 9060A) – Carbonaceous Analyzer; Direct Method 10173 (Hach, 2019)	Total Organic Carbon (Analyzer Vario TOC cube, Germany)
Ultimate properties			
Elementary of carbon (C), hydrogen (H), nitrogen (N), sulphur (S), oxygen (O)	%	Perkin Elmer 2400 CHNS/O Analyzer (Method: 2mgChem80s)	Ultra-Centrifugal Grinding Machine (Retsch ZM200, Germany); Organic Elemental Analyzer (PerkinElmer 2400 CHNS/O Series II Analyzer, USA)

yield for OFMSW accounts for 75% of total VS. Therefore, the left-over 25% or 0.25 of VS is left for biofertilizer yield.

$$F_{bio} = \frac{[(DM - VS) + (0.25 \times VS)] \times Morganic}{100} \quad (6)$$

where, F_{bio} = bio-fertilizer yield, kg/day; DM, dry mass % = mass of organic solids (weight after 24 h of oven at 105 °C); VS, volatile solids % = fraction of DM converted into biogas (weight after 1 h of furnace at 550 °C); $M_{organic}$ = mass of organic waste inflow, kg/day.

3.4. Environmental protection: avoidance in CO_2, leachate and land-use

The CO_2 emissions avoidance was determined by Eq. (7) (SEDA, 2019), while reduction in landfilling surface area and leachate avoidance were determined by Eqs. (8) and (9) (Ibrahim et al., 2017) respectively:

$$CO_2 = C_C \times E_{bio} \quad (7)$$

where, CO_2 = CO_2 avoidance, t/day; C_C = baseline constant for offsetting CO_2 by producing electricity from renewable in Peninsular Malaysia, t/MWh; E_{bio} = electrical energy output, kWh/day.

$$A = M_{organic} \times \frac{1}{B} \times \frac{1}{H} \quad (8)$$

where, A = area required to landfill organic waste, m^2/day; $M_{organic}$ = mass of organic waste inflow, t/day; B = compacted density of municipal solid waste, t/m^3; H = depth of landfill, m.

$$V = 0.15 \times R \times A\ (m^2) \quad (9)$$

where, V = volume of leachate discharge, m^3/day; R = annual rainfall, m; A = area required to landfill organic waste, m^2/day.

3.5. Economic feasibility analysis

The economic analysis holistically considers the supply chain. Therefore, the methods used to calculate the total expenses and total revenue from OFMSW biogas project are shown in Table 2.

Based on the information gathered from Sustainable Energy Development Authority Malaysia, the initial capital expenditure (CAPEX) for the anaerobic biogas power plant is inclusive of the digester equipment, gas engine, generator, balance of system, installation cost, design and consultancy, interconnection cost (from plant to nearest national utility substation), preliminary cost and other capital costs (Yong et al., 2019). For the and annual operation and maintenance expenditure (OPEX), the cost for insurance premium, anaerobic digestion plant and gas engine operation and maintenance expenditure, fuel cost at site and other operating costs are considered. Furthermore, the costing information for the CAPEX (RM 7.08 million) and OPEX (RM 1.1 million) per MW of biogas system installation was provided by SEDA Malaysia.

4. Results and discussion

4.1. Quantity and characterization of OFMSW

Concerning implementation of the anaerobic digestion, it could be difficult to achieve 100% collection and conversion of organic waste. In this study, experts indicated that only 50% of the generated OFMSW was considered due to the potential losses of OFMSW during collection and transportation stages. The laboratory analysis of the collected OFMSW was categorized into three categories namely physical, chemical, and ultimate properties. The results of OFMSW characteristics are summarized in Table 3.

As can be seen in Table 3, most parameters of the OFMSW samples are in agreement with results reported by other researchers. The biogas composition (CH_4 to CO_2 ratio), biogas volume yield, dry matter (DM), volatile solid (VS) and elementary properties of OFMSW were tested. Therefore, the average value obtained were 44.60% DM, 29.66% VS while the elementary results namely the weight percentage of C, H, N, S and O were 47.03%, 6.75%, 2.58%, 0.52% and 32.7% respectively. Moreover, the chemical oxygen demand (COD), ammoniacal nitrogen (NH_3-N) and total organic carbon (TOC) content of the analyzed OFMSW were found to be 393,405 mg/L or 62,880 mg/kg, 347 mg/L or 55.52 mg/kg and 34,210 mg/L or 5473.6 mg/kg, respectively. The findings for COD, NH_3-N and TOC are in good agreements with previous literatures (Angeli et al., 2018; Fisgativa et al., 2016).

4.2. Composition and volume of biogas

Based on the results obtained from the ultimate analysis, the composition of CH_4 to CO_2 was found to be 56.62% and 43.38% respectively. The composition of CH_4 and CO_2 found in this study was in range of typical biogas composition where CH_4 normally accounts for 55–65%, CO_2 accounts for 35–45% (Bong et al., 2018; Jutidamrongphan, 2018). The volume of biogas and pure CH_4 gas yield, V_{CH4} are shown in Table 4. Based on the laboratory characterization of OFMSW and calculations, this study indicated that an average of 396 L of pure CH_4/kg VS will be produced, in which our result is comparable to the 255–591 L CH_4/kg VS gathered from various real field applications of solid organic waste anaerobic digester implemented mostly in Europe, China, Japan and Korea as reported by Angeli et al. (2018), Bissmont et al. (2015), Davidsson et al. (2007), Fisgativa et al. (2016), Negri et al. (2020) and Xu et al. (2018).

To obtain a stable and good yield of biogas and fertilizer, the operation of the biogas plant is utmost crucial. Table 5 summarizes the various crucial operational conditions and parameters in accordance with the information provided by several literatures and real anaerobic digester biogas project, in which these plants need a real-time monitoring system with sensors and probes attached and embedded in the anaerobic digestion bioreactor.

4.3. Electrical energy-power and biofertilizer generation

The electrical energy produced from biogas, E_{bio} and the effective electrical power or capacity of the biogas power plant, P_{bio} were

Table 2
Estimation of total expenses and revenue from OFMSW biogas project.

Financial parameter		Formula	Equation no.
Expenses	Capital expenditure (CAPEX)	$Expenses_{CAPEX}$, RM = RM 7.085 million/MW × P_{bio}, electrical power output, MW	(10)
	Operating expenditure (OPEX)	$Expenses_{OPEX}$, RM/year = RM 1.1 million/MW/year × P_{bio}, electrical power output, MW	(11)
	Tipping fees	$Expenses_{Tipping}$, RM/day = RM 78.54/t × $M_{nonorganic}$, incoming mass of non-OFMSW, t/day	(12)
Revenue	Biogas-electricity	$Sales_{Electricity}$, RM/day = RM 0.3997/kWh × E_{bio}, electrical energy output, kWh/day	(13)
	Bio-fertilizer	$Sales_{Fertilizer}$, RM/day = RM RM515/t × F_{bio}, bio-fertilizer yield, t/day	(14)
	Landfill OPEX	$Saving_{Landfill}$, RM/day = RM 42/t × $M_{organic}$, incoming mass of OFMSW, t/day	(15)
	Leachate treatment	$Saving_{Leachate}$, RM/day = RM 418.94/day × V = volume of leachate discharge, m^3/day	(16)

Note: 1 US Dollar ≈ 4.15 RM.

Table 3
Characterization results of Malaysia's OFMSW.

Analysis	Properties	Unit	Value - range	Value - average	Standard value (ref.)
Proximate	*Physical properties*				
	pH	–	4.47–4.81	4.59	4.02–7.17 (Bong et al., 2018; Negri et al., 2020)
	Oxidation reduction potential (ORP)	mV	141.83–146.80	145.11	–
	Temperature	°C	26.4–27.4	27.0	–
	Total solids (TS)	%	20.90–43.95	22.11	7.94–40.0 (Bong et al., 2018; Negri et al., 2020)
	Volatile solids (VS)	%	20.29–43.05	29.66	6.74–39.2 (Bong et al., 2018; Negri et al., 2020)
	Moisture content (MC)	%	48.18–60.08 (Wet basis)	55.40	21.15–85.6
	Dry matter (DM)	%	39.92–51.82	44.60	–
	Chemical properties				
	Calorific value	kJ/g	19.97–22.31	20.88	16.75–29.86 (Komilis et al., 2012)
	Chemical oxygen demand (COD)	mg/L	290,608–587,630	393,405	198,000–297,210 (Angeli et al., 2018; Fisgativa et al., 2016)
	Ammoniacal-nitrogen (NH_3-N)	mg/L	239–478	347	5.08–301 (Angeli et al., 2018)
	Total organic carbon (TOC)	mg/L	34,210		–
Ultimate	*Elementary properties*				
	S	%	S = 0.52%		S = 0.1–0.9%
	N		N = 2.58%		N = 1.5–3.9%
	H		H = 6.75%		H = 5–7.66%
	O		O = 32.7%		O = 32.7–37.6%
	C		C = 47.03%		C = 37.6–51.3%
					(Tyagi et al., 2018; Firdaus et al., 2018; Negri et al., 2020)

Table 4
The volume of biogas and pure methane gas based on 50% collection of OFMSW.

Parameter		Unit	Value
Input	C	gC/gVS	0.375
	CH_4	%/100	0.5662
	M_{carbon}	g/mol	12
	V_{STP}	L/mol	22.4
	VS	%/100	0.2966
	$M_{organic}$	kg/day	11,175,750
Output	V_{CH4}	m^3/day	985,405
	Biogas	m^3/day	1,740,231

calculated based on Eq. (4) as shown in Table 6. The practical efficiency of the biogas engine is set to be 40% according to the commercial Jenbacher gas engine catalogue. Eq. (5) was used to cross-check the biogas electrical energy, E_{bio} and power, P_{bio} as shown in Table 7. The calculated E_{bio} and P_{bio} from both formulas show similar results with little difference of only 0.41%. The final average E_{bio} and P_{bio} obtained from both formulas were 3941 MWh/day and 164 MW, respectively. Similarly, the average electrical energy output per tonne of OFMSW was 353 kWh/t which is comparable to other literature reported 220–404 kWh/t (Thi et al., 2016; Surroop and Mohee, 2012).

The biofertilizer potential, F_{bio} was estimated to be at 2500 t/day for 50% OFMSW collection based on Eq. (11) as shown in Table 8. Previous study confirmed that the nutrient content such as nitrogen, phosphorus, and potassium of the produced solid and liquid biofertilizers from AD meet the biofertilizer standards, while hazardous content in terms of heavy metal and other pathogenic bacterial like *E. coli* and ascarid egg were found to be within the acceptable limit (Ma et al., 2020).

Table 5
The key parameters during the operation and monitoring of an anaerobic biogas power plant system (Albanna, 2013; Khalid et al., 2011; Seadi et al., 2008; Van et al., 2019).

Parameter	Symbol	Unit	Optimal value/range	Determination
Temperature	T	°C	37–51	Measurement during operation
pH	pH	–	6.5–7.5	
Pressure	P	mbar	N/A	
Gas quantity	V	m^3/day	N/A	
Methane fraction	CH_4	%	50–70	
Moisture content	MC	%	60–80	
Carbon to nitrogen ratio	C/N	–	20–30	
Nutrients	C:N:P:S	–	600:15:5:3	Calculation from operation data
Retention time	RT	days	15–30	
Hydraulic retention time	HRT	days	15–30	
Solid retention time	SRT	days	>20	

4.4. Environmental analysis

The CO_2 avoidance, landfilling area avoidance and leachate avoidance are summarized in Table 9. A total of 2735 t of CO_2 avoidance can be achieved daily by using OFMSW to generate renewable electricity in Malaysia. The factor C_c = 694 kg CO_2/MWh is the baseline for CO_2 emission in generating per MWh of electricity in Malaysia (SEDA, 2020). The C_c is the overall greenhouse gas emitted from fossil fuel power stations which can be offset using renewable resources such as solar, biogas, and biomass to generate electricity back to the electrical grid system. The constants B and H are average compacted waste density for landfilling is 450 kg/m^3 (Selamat and Aziz, 2016; Foday et al., 2017) and landfill depth of 22 m (Younes et al., 2015) respectively.

Table 6
The electrical energy and power potential yield from the generated biogas-Methane based on 50% collection of OFMSW.

Parameter		Unit	Value
Input	V_{CH4}	m^3/day	985,405
	E	kWh/m^3	10
	N_{el}	%	40
Output	E_{bio}	MWh/day	3941
	P_{bio}	MW	164

Table 7
The cross-check of the biogas-to-electrical energy and power potential based on 50% collection of OFMSW.

Parameter		Unit	Value
Input	$M_{organic}$	kg/h	465,656
	Y	m^3/kg	0.1557
	D	%	56.62
	P	kg/m^3	0. 717
	LHV	MJ/kg	50
	C	–	0.2778
	N_{el}	%	40
Output	E_{bio}	MWh/day	3925
	P_{bio}	MW	163.5

Table 8
The bio fertilizer yield based on 50% collection of OFMSW.

Parameter		Unit	Value
Input	DM	%	44.60
	VS	%	29.66
	$M_{organic}$	Mg/day	11,175
Output	F_{bio}	Mg/day	2500

Table 9
Contribution to environmental protection based on 50% collection of OFMSW.

Parameter		Unit	Value
Input	C_C	kg CO_2/MWh	694
	E_{bio}	MWh/day	3933
	$M_{organic}$	t/day	11,175
	B	t/m^3	0.45
	H	m	22
	R	m	2.84
Output	CO_2 emission reduction	t/day	2735
	Landfill area saving	m^2/day	1128
	Leachate avoidance	m^3/day	481

While the latest average annual rainfall in Malaysia according to Malaysian Meteorological Department (Jabatan Meteorologi Malaysia) is 2.84 m (MET, 2020). Therefore, the potential in the reduction of land area for landfilling OFMSW was 1128 m^2/day while the reduction in leachate formation from landfills was 481 m^3/day.

4.5. Economic analysis

The economic analysis of this study takes in to account the total expenditure versus total revenue hence the net profit that can be generated and the return of investment (ROI). In terms of total expenditure, the cost of MSW services is inclusive of the collection, transportation and landfilling of waste together with the initial capital expenditure (CAPEX) and operational expenditure (OPEX) of the biogas power plant. While the revenue generated includes the total sales of selling back the generated renewable electricity into the electricity grid via FiT, the sales of biofertilizer to local agriculture players plus savings in the cost of landfilling OFMSW and leachate treatment. According to MHLG (2015), the average cost in Malaysia for MSW collection, transport and landfill disposal are RM 66/t/day, RM 40/t/day and RM 42/t/day respectively. Therefore, total cost for non-OFMSW landfilling is RM 148/t.

In terms of revenue, renewable electricity generated from waste (biogas) is sold to the Malaysian utility company (Tenaga National Berhad, TNB) via the national electricity grid at a FiT rate of RM 0.3997/kWh (SEDA, 2020) while the average market value of organic fertilizer is sold at RM 515/t (Malaysia.tradekey.com, 2019). The savings from landfilling OFMSW is the same cost for landfill disposal (RM 42/t/day) while the savings in leachate treatment is found to be RM 5.69/m^3 via traditional wastewater treatment system (García et al., 2014). Table 10 summarizes detail parameters of economic analysis.

By converting all financial parameters from daily to yearly, the return of investment (ROI) of the OFMSW-to-energy and fertilizer via anaerobic digestion project was determined. The general formula for calculating the ROI of the OFMSW biogas project as follows:

$$\text{ROI} = \frac{Total\ Initial\ Investment\ (RM)}{Net\ Profit\ \left(\frac{RM}{year}\right)}$$

$$\text{ROI} = \frac{1161.22\ million\ (RM)}{297.66\ million\ \frac{RM}{year}} = 3.9 \approx 4\ \text{years}$$

In this study, the ROI in years was determined by plotting the cumulative expenditure versus cumulative revenue as presented in Fig. 3. The intersection point in Fig. 3 is the point of ROI or point of breakeven where the net profit is enough to cover all initial investment including the landfill tipping cost for non-OFMSW. Hence, the ROI in years was found to be 4 years.

4.6. Anaerobic digestion of OFMSW towards achievement of the UN-SDGs

A complete anaerobic digestion biogas power plant is a complex system which consists of mainly mechanical, electrical, and biological subsystems with a pre-treatment system upfront. Therefore, Fig. 4 which is being inspired by (AZEUS Fertilizer Machinery, 2018; Blischke, 2009; Moestedt et al., 2013; Moustakas et al., 2020) illustrates the overall components comprises within a full-scale operation biogas power plant system which used solid biodegradable waste or OFMSW to generate electricity via the combustion of biogas produced from anaerobic digestion tanks. AD biogas power plant system can be generally divided into 3 sub-systems namely pre-treatment system, biological system, and mechanical and electrical system. In the pre-treatment system, OFMSW feedstock should be transported and collected in the biomass collection tank. Then, OFMSW is to pass through the electromagnetic-screening, crusher and mixing tank to remove all non-organic constituents before entering the equalization tank. The equalization tank is to fine-tune the OFMSW parameters namely pH, nutrient content, reduction in toxicity and etcetera to ensure the feedstock is suitable and at optimal condition for the digesting process. In the biological system, the OFMSW is digested in the anaerobic digestion tank by specialized anaerobic microbes to produce high quality raw biogas. The raw biogas containing roughly 60% CH_4 and 40% CO_2 with other trace gases is needed to be filtered by the biogas filtration system to purge out all other gases to obtain CH_4. In the mechanical and electrical system, the treated biogas to be combusted in the biogas engine excess exhaust gas is to be released into the atmosphere via exhaust duct. The rotational kinetic energy generated from the biogas engine is to be converted into electricity via the generator. The generated electricity is to be fed into the bi-directional electrical meter to be sold back to the utility company. Finally, the generated digestate after the digestion process will be dewatered and compost into bio-fertilizer is to be collected in a bio-fertilizer tank. The biofertilizer can be used and sold as nutrient rich fertilizer for agriculture applications. To effectively increase on the total collection of OFMSW in Malaysia, the Malaysian government will need

Table 10
Summary and detail parameters of economic analysis.

Parameter		RM/unit	Total amount	Total value (million RM/year except CAPEX, one time only)
Expenses	Capital expenditure (CAPEX)	$7.08 * 10^6$/MW	164 MW*	1161
	Operating expenditure (OPEX)	$1.1 * 10^6$/MW/year	163.9 MW	180.3
	Landfill tipping fees	148/t	13,659 t of non-OFMSW/day	737.9
Revenue	Sales of biogas-electricity	0.3997/kWh	3,933,567 kWh/day	573.9
	Sales of bio-fertilizer	515/Mgt	2498 t/day	470
	Savings in landfill OPEX	42/t	11,176 t of OFMSW/day	171
	Savings in leachate treatment	5.69/m^3	481 m^3/day	1.0

M*/MW* = Million RM/megawatt.

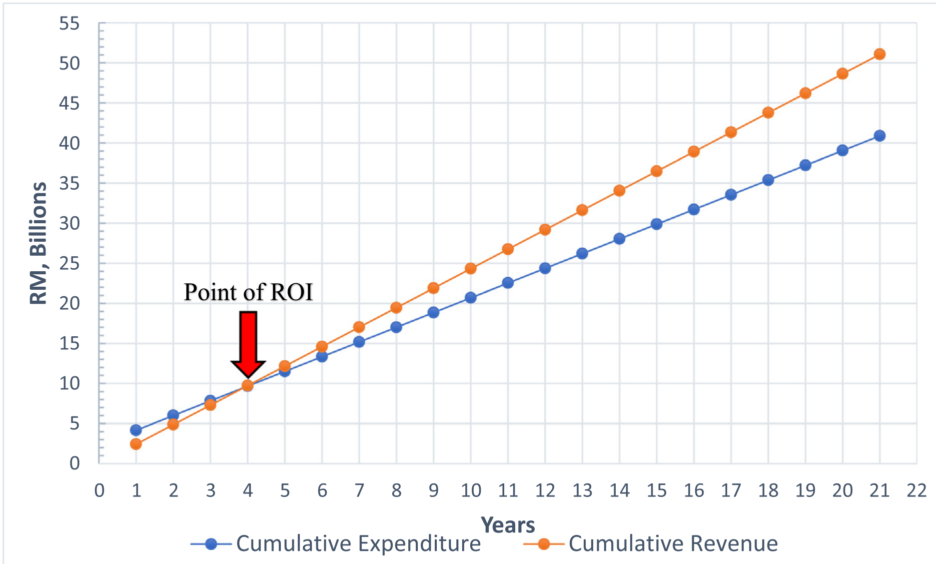

Fig. 3. The return of investment (ROI) of the OFMSW-to-Energy and Fertilizer in Malaysia.

to enforce on the waste management policy and to cooperate with commercial, industries and ultimately household residents towards waste segregation practices at source. Therefore, the various output of integrating AD of OFMSW into nationwide solid waste management directly affects the 3 pillars of economic development, social inclusiveness, and environmental sustainability in the context of sustainable development due to various transboundary nature of SWM affecting sanitation, public health, natural ecosystem, livelihood, sustainable use of natural resources and admittance to decent jobs (Rodić and Wilson, 2017). By implementing nationwide source segregation of OFMSW and anaerobic digestion; this project will contribute to at least 10 identified United Nations Sustainable Development Goals as illustrated in Fig. 5. By diverting and recovering all OFMSW from landfills and various sources respectively in Malaysia the 3Es (Environment, Energy and Economic) co-benefit can be summarized Fig. 6. Dada and Mbohwa (2018) reported that the energy recovered from waste directly contribute to sustainable development goal no.7 – clean energy. Rahman et al. (2019) concluded that implementation of bioenergy system can meet various national development of economic, environmental, health, social and cultural at the same time contribute (goal no. 3, 4, 5 and 7). The avoidance of highly contaminated leachate can contribute to the public health (Azmi et al., 2016). The world biogas association, reported that anaerobic digestion of organic

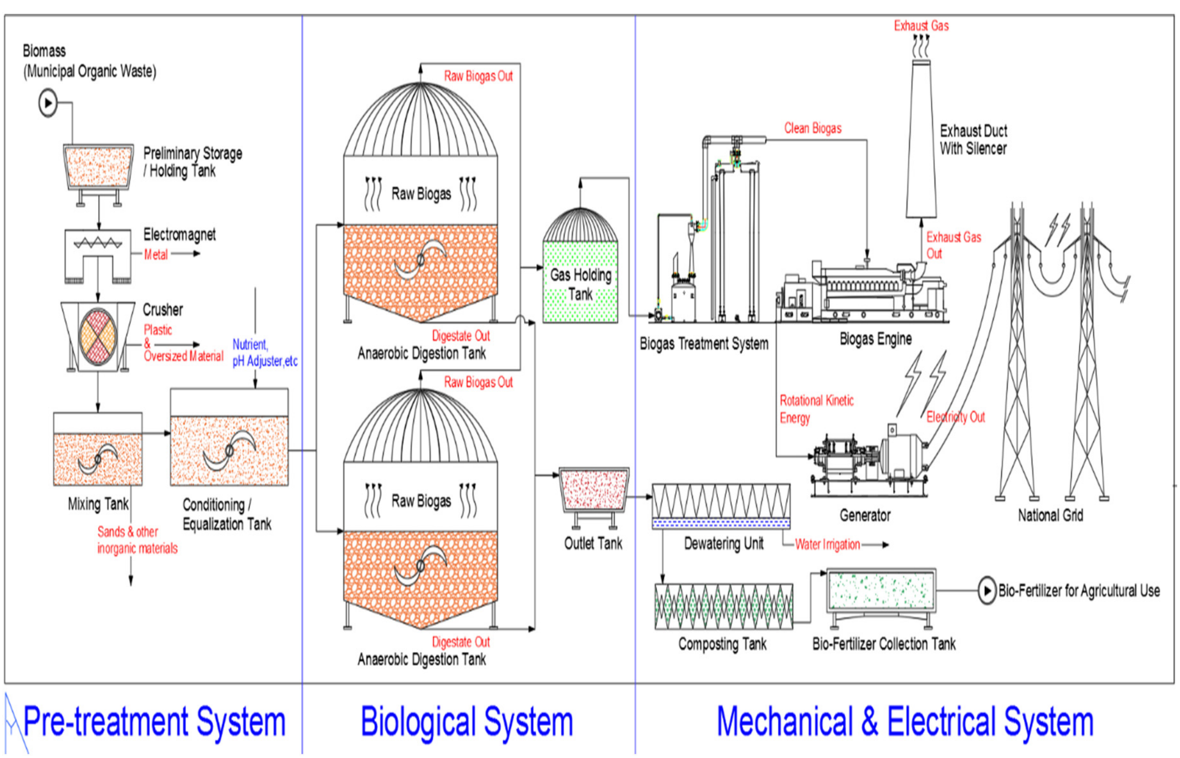

Fig. 4. The proposed schematic overview of an anaerobic digestion biogas with digestate recovery power plant system for household organic fraction municipal solid waste as feedstock.

Fig. 5. The 10 United Nations Sustainable Development Goals that is related to bioenergy recovery from waste.

waste directly contribute in meeting the sustainable development goals no. 6 – ensure availability and sustainable management of water and sanitation; no. 7 – ensure access to affordable, reliable, sustainable and modern energy; no. 11 – make cities and human settlements inclusive, safe, resilient and sustainable; no. 13 – take urgent action to combat climate change and its impacts and no. 15 – protect, restore and promote

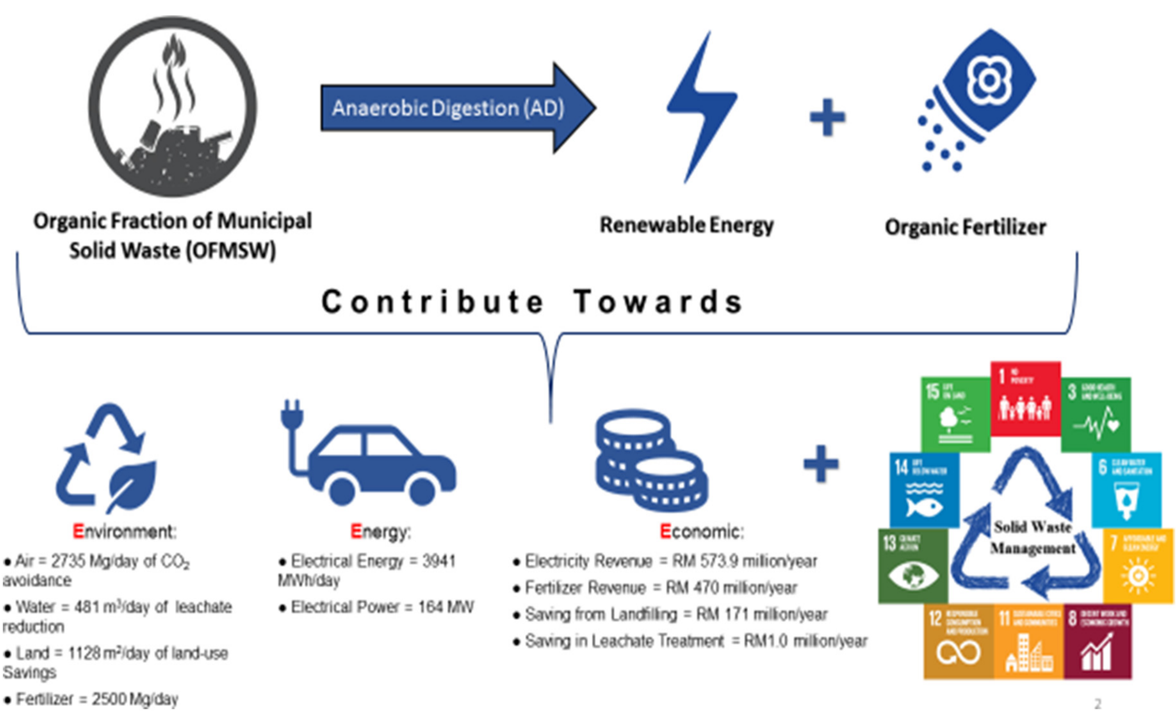

Fig. 6. The summary of 3E (Environmental, Energy and Economic) results of converting OFMSW into renewable electricity and biofertilizer.

Table 11
Summary of the relationship between and OFMSW biogas project waste management in Malaysia and United Nations SDGs.

Sustainable development goals (SGDs)	SDG target/relationship description	Quantifiable numbers
• No. 1-No Poverty • No. 8-Decent work & Economic Growth	1.2: By 2030, reduce at least by half the proportion of men, women and children of all ages living in poverty. 8.2: Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, with a focus on high value added and labor-intensive sectors	• An average 25 jobs created average during all phases of biogas project (SEDA, 2019). • Biogas industries have highest direct employment rates (DER) of 5.69 per 1 MW installed capacity (Lavrencec, 2010; Sukkumnoed et al., 2018):
• No. 3-Good Health & Well-Being	3.9: By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination	• Reduce potential risk of landfill air pollution, leachate pollution of 481 m^3/day. • Land contamination of 1128 m^2/day of diverting OFMSW from landfills.
• No. 6-Clean Water & Sanitation • No. 14-Life Below Water	6.3: By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, etc. 14.1: By 2025, prevent and significantly reduce marine pollution of all kinds, from land-based activities.	• Water pollution is potentially avoided from landfilling OFMSW, leachate avoidance of 481 m^3/day.
• No. 7-Affordable & Clean Energy	7.2 By 2030, increase substantially the share of renewable energy in the global energy mix	• Renewable electricity from OFMSW: 3941 MWh/day
• No. 11-Sustainable Cities & Communities	11.6: By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	• Annual diversion of $4.08 * 10^6$ t OFMSM from landfills to produce: −164 MW of electricity power capacity • Generating 2500 t/day bio fertilizer
• No. 12-Responsible Consumption & production	12.2: By 2030, achieve the sustainable management and efficient use of natural resources 12.4: By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle and reduce their release to air, water and soil to minimize their adverse impacts on human health and the environment	• OFMSW as a renewable energy source to generate electricity: - Clean electricity = 3941 MWh/day • Diverting OFMSW from landfill hence reducing landfill's environmental impacts:
• No. 13-Climate Action	13.2: Integrate climate change measures into national policies, strategies, and planning	• Avoiding direct release of Methane gas, CH_4 into atmosphere hence reduce in GHGs.
• No. 15-Life on Land	15.1: By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, forests, wetlands, mountains and drylands.	• Extending lifespan of existing landfills. • Reduce land-use for landfilling OFMSW by 1128 m^2/day

sustainable use of terrestrial ecosystem, sustainably manage forest (Worldbiogasassociation.org., 2018). Table 11 summarizes the 10 SDGs.

5. Conclusion

Resource recovery organic fraction municipal solid waste in Malaysia via anaerobic digestion can significantly contribute towards the environment sustainability, renewable energy expansion and positive economic development. The potential avoidance in CO_2 emission, landfilling area and leachate generation were found to be 2735 t of CO_2/day, 1128 m^2/day and 481 m^3/day respectively. The potential renewable bio-energy production from biogas with 56.62% CH_4 and 43.38% CO_2 was 3941 MWh/day. Moreover, the organic fertilizer yield was found to be 2500 t/day. Based on the financial analysis of total revenue versus total expenditure, the return of investment was found to be within 4 years. Consequently, the implementation of multiple biogas facilities for organic fraction municipal solid waste anaerobic digestion can encourage a positive paradigm shift in the Malaysian solid waste management towards a more sustainable practice with an economic revenue generating activity. The biogas project complements with numerous he sustainable development goals including clean water & sanitation, affordable & clean energy, sustainable cities & communities, responsible Consumption & production, climate Action, and etc.

To obtain a more accurate analysis on the environment, energy and economic factors as well as the feasibility study on the implementation of such project in Malaysia, the following are recommendations needed to further investigate:

i) *In-cooperating co-digestion:* Other organic waste from other sources can improve the biogas yield and stability of the digester. Industry, agriculture, live-stock waste (manure, blood, organs), sewage treatment (sludge) as co-digestion which can improve the yield of biogas (Sosnowski et al., 2003; Tyagi et al., 2018).
ii) *Comprehensive pre-treatment/screening facility study and selection:* Since organic fraction municipal solid waste is complex and heterogeneous in nature, various types of commercially available pre-treatment systems are needed to be compared to select the most practical and economic solution to ensure only suitable organic fraction municipal solid waste enters into the digester to avoid chocking of the digester.

CRediT authorship contribution statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript.

Declaration of competing interest

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

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