DEVELOPMENT OF A TECHNICAL AND ECONOMIC FEASIBILITY STUDY FOR ANAEROBIC DIGESTION OF THE ORGANIC FRACTION OF SOLID WASTE FROM HOUSEHOLDS, HOTELS AND MARKETS IN MAURITIUS

OUTPUT 3: ANAEROBIC DIGESTION ANALYSIS INCLUDING QUANTIFICATION OF BIOGAS/METHANE AND ENERGY PRODUCTION POTENTIAL

Submitted to:

Climate Technology Centre & Network (CTCN)

Department of Environment, Ministry of Environment, Solid Waste Management & Climate Change, Republic of Mauritius

Solid Waste Management Division, Ministry of Environment, Solid Waste Management & Climate Change, Republic of Mauritius

Submitted by:

Council for Scientific and Industrial Research (CSIR)

University of Mauritius (UoM)

Technical Assistance Ref. No.: CTCN 2020000014
Budget line: S1-32CLL-000010; SB-000900.13.02.12

Issue: v1.1

Date: 06 October 2021

Contents

Acronyms

AD	Anaerobic Digestion
ADM1	Anaerobic Digestion Model No. 1
BMP	Biochemical Methane Potential
FSMY	Full Scale Methane Yield
FW	Food Waste
MBT	Mechanical Biological Treatment
MD	Methane degradability
MSW	Municipal Solid Waste
ss-OFMSW	Source Sorted Organic Fraction of Municipal Solid Waste
OFMSW	Organic Fraction of Municipal Solid Waste
TBMP	Theoretical Biochemical Methane Potential
TPD	Tonnes Per Day
TPY	Tonnes Per Year
TS	Total Solids
VS	Volatile Solids
WtE	Waste to Energy
YW	Yard Waste
TKN	Total Kjedahl Nitrogen

Overview of Deliverable 3

The third deliverable is divided into two parts:

- Quantification of biogas and energy production potential.
- Identification, quantification, and valorisation of by-products.

The deliverables for Output 3, i.e., activities 3.1 and 3.2, are presented in this report. The previous study on Output 2 quantified and characterized the organic fraction of municipal solid waste that is generated in Mauritius. Output 3 focused on determining the biogas/methane production from the solid organic fraction waste, including quantifying the electricity generation and heat recovery potential from 100 tons/day anaerobic digestion of food waste (FW) supplemented by yard waste (YW). The calculations were based on the quantities and characteristics determined in Output 2. The work further explored the potential of recovering liquid and solid fertilizers, and any other valuable by-products from the digestate.

1 Introduction

Municipal solid wastes (MSW) are an inevitable part of daily life activities, with more than 2.01 billion tonnes of such waste generated worldwide annually (Kaza, Yao, Bhada-Tata & Van Woerden, 2018). The management of MSW is increasingly becoming a pressing issue for governments across the globe. This is because unsafe disposal of such waste has negative impacts on both human and animal health (including livelihoods), and leads to pollution of both air, land, groundwater and water bodies (rivers, lakes). Besides, issues related to the disposal or management of MSW are exacerbated in insular territories due to the land mass limitation. Furthermore, biodegradable waste contained in such waste degrades naturally, emitting potent greenhouse and ozone depleting gases that contribute towards global climate change.

Small islands developing states (SIDS) like Mauritius have not been spared from this problem of waste disposal. As it's consumerism-driven economy and human population continues to grow, this will lead to increased generation of waste products prompting for development of sustainable waste management. Furthermore, Mauritius' energy needs are primarily reliant on fossil fuels, with renewable energy accounting for only a small portion of the island's total primary energy requirements. This problem has prompted government to develop interventions to sustainably manage and dispose waste.

One of the key interventions that governments across the globe are considering in waste management value chain is recovering resources that have economic value from waste, thereby reducing the amount of waste that is sent to landfills. There are number of technologies that can be employed in recovering resources from waste which include the following:

- Landfill gas extraction through extraction wells systems at sanitary landfills.
- Incineration for thermal energy recovery
- Composting of waste for recovery of fertilizers for various land applications.
- Anaerobic digestion(AD) of organic fraction of the municipal solid waste (OFMSW) for biogas generation for subsequent electricity generation, and production of liquid and solid fertilizers.
- Recovery of refuse derived fuel (RDF)

The Mauritian government is now moving towards composting and recycling as an intervention to reduce the amount of waste that is sent to Mare Chicose landfill. The Mare Chicose Landfill is the only landfill on the island that the MSW generated is disposed at. It is a sanitary landfill that is equipped with gas wells system for harvesting of landfill gas for electricity generation. In 2019, 19.8 GWh/year of electricity was generated from landfill gas which is 0.6% of electricity consumed on the island (CSIR & UoM, 2021).

However, given that the landfill is near its saturation point, AD of OFMSW can reduce the amount of waste sent to the Mare Chicose Landfill (CSIR & UoM, 2021). This study focused on investigating the financial viability of implementing waste to energy (WtE) project that focuses on generating biogas and energy from OFMSW, recovery of liquid and solid waste fertilizers for use on the island. This document reports on the activities under Output 3, which are components of the "*Development of a technical and economic feasibility study for anaerobic digestion of the organic fraction of solid waste from households, hotels and markets in Mauritius*". The activities were focused on determining biogas/methane production and electricity generation potential from 100 tonnes/day AD plant for treatment of food waste as a main component, and further, identifying and quantifying other valuable by-products that can be recovered thereof.

2 Background

2.1 Anaerobic Digestion

AD refers to the microbial degradation of organic matter in the absence of oxygen to produce biogas (i.e. methane) and a digestate. AD involves the breakdown of organic matter by anaerobic micro-organisms in the absence of oxygen. The breakdown releases biogas, a mixture of gases of composed mainly of methane and carbon dioxide, and lower concentration of hydrogen, water vapour, hydrogen sulphide, ammonia, and siloxanes. The biogas can be used directly for cooking, in a combined heat and power (CHP) plant for electricity generation and heat recovery or upgraded to bio-methane for use as transport fuel. The digester effluent supernatant (depending on the level of toxic contaminant and pathogenic concentration) can be used as liquid fertilizers for application on agricultural farms. The digestate can be used as an organic fertiliser or composted with fresh wastes.

Common feedstocks that have been subjected to the AD process include organic fraction of municipal solid wastes, food wastes, yard wastes, agricultural residues (e.g., straws), animal manures, municipal sewage sludge, industrial wastewaters and slaughterhouse wastes, amongst others. AD is a multi-step reaction involving a wide range of microorganisms working in synergy for breakdown of organic matter as shown in Figure 1. The reaction proceeds in four steps (phases) namely:

Hydrolysis

During this first step, high molecular weight compounds like carbohydrates, proteins and fats are broken down by facultative or obligatory anaerobic bacteria into their soluble organic components namely simple sugars, amino acids and fatty acids, respectively (Appels et al., 2008).

Acidogenesis

During the second stage of acidogenesis, the components produced from the hydrolytic phase are further broken down by facultative or completely anaerobic acidogens into short-chain fatty acids, alcohols, H_2 and CO_2 (Deublein and Steinhauser, 2008).

Acetogenesis

In the third phase, acetogens convert the short-chain fatty acids and alcohols from the acidogenic phase into acetic acid, CO_2 and H_2 (Appels et al., 2008).

Methanogenesis

In the final phase of methanogenesis, completely anaerobic methanogens convert the acetic acid and H_2 into methane and carbon dioxide (Deublein and Steinhauser, 2008).

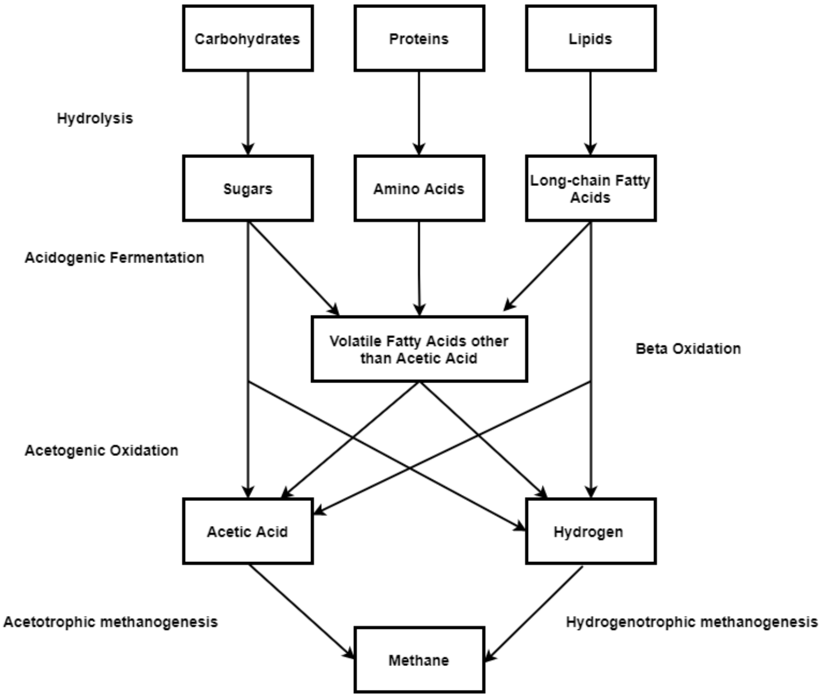


Figure 1: Reaction mechanism of anaerobic digestion (adapted from Al Mamun, 2015)

2.1.1 Biogas/Methane determination of substrates

The amount of biogas/methane that can be generated per unit mass of a substrate (biogas/methane yield) is dependent on feedstock composition and process parameters. The biogas/methane yield can be calculated theoretically using feedstock characteristics as an input. It can also be measured directly by biochemical methane potential (BMP) or continuous fermentation experiments. The theoretical biogas yields are simple to measure but less accurate to yields measured in experiments, this is because the theoretical estimations do not consider operational parameters.

Theoretical Yield Calculations

There are various mathematical models that can be applied to calculate the biogas production from the feedstock. The models have different level of accuracies that increases with increased application complexities. More accurate models require measurement of more feedstock characteristics and operation conditions, which requires increased invested financial resources and time. Figure 2 shows the trend between the accuracy and application complexities.

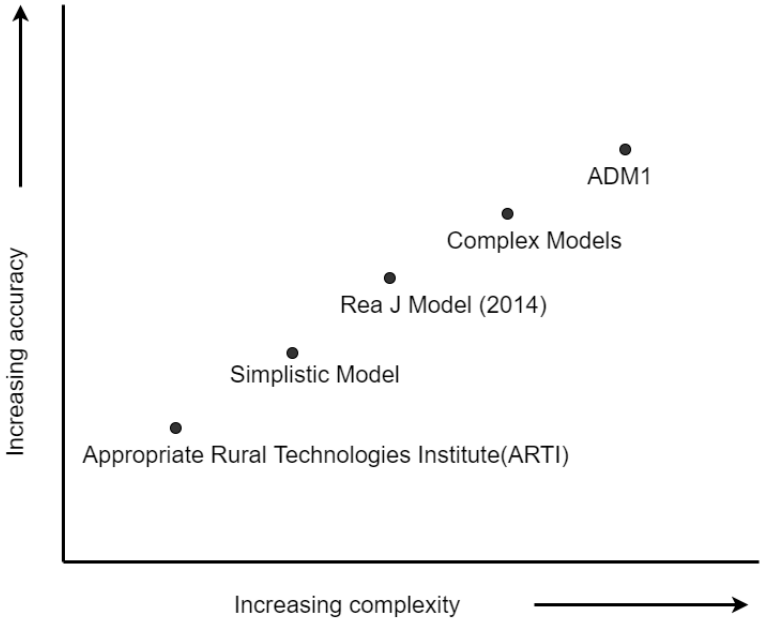


Figure 2: Various AD simulation models

Anaerobic Digestion Model No.1 (ADM1) developed by the International Water Association is one of the most accurate and widely applied model.

2.1.2 Process parameters

There are several parameters of the AD process that can be adjusted or monitored to enhance biogas production, and these include hydrogen partial pressure within the digester, concentration of microorganisms, types and number of substrates used, surface area or size of feedstocks, presence of light, presence of oxygen, hydraulic retention time, operating temperature and pH, and the nutrient levels (Deublein and Steinhauser., 2008). Among these, the following main process parameters are overviewed.

- **Presence and concentration of foreign materials**

The presence of inorganic or slowly biodegradable material (i.e., glass, metals, plastics) can render the AD process unstable (Fei et al., 2018). As such, these materials must be removed from the feedstock prior to loading into digester. Given that there is no currently separation of the waste at source, the waste is mixed with other materials that would need to be removed prior to digestion. However, the Solid Waste Management Division is planning to implement waste segregation at source followed by separate collection of waste. Food waste will diverted to the AD plant with supplementation of yard waste. At the initial stages of the collection system, the purity of the waste might be poor requiring pre-treatment of the waste prior to AD to remove unwanted materials.

- **pH**

pH is an important parameter of the AD process as this can lead to process failure, if not properly monitored. pH is an indication of the concentration of hydrogen ions in the biodigester which are formed because of the production of volatile fatty acids. Among the different microorganisms present in a biodigester, the methanogens are the most vulnerable to low or high pH and these thrive in a small pH range of 6.7 to 7.5 (Deublein and Steinhauser, 2008). As for the microorganisms within the hydrolytic and acidogenic phases, these are more effective at a pH of 6.5 (Kim et al., 2003). To prevent pH drop in a digester and thus prevent process failure due to inhibition of the activities of the methanogens, it is important to control the pH within the digester. This can be done by either providing sufficient buffering capacity in the system through increasing the alkalinity of the substrates by adding calcium carbonate or by adjusting the pH automatically through sensors and through the use of lime.

- **Temperature**

Temperature has an impact on the growth and activities of microorganisms and thus, has a direct influence on bio-methane production (Appels et al., 2008). There are three temperature ranges that have been investigated for bio-methane production from organic wastes namely psychrophilic temperatures (10 to 20^{o}C), mesophilic temperatures (20 to 45^{o}C) and thermophilic temperatures (50 to 65^{o}C) (Kothari et al., 2014). Thermophilic temperatures are reported to have higher rates of pathogen destruction and shorter retention times (Appels et al., 2008; Panigrahi and Dubey, 2019) as well as higher substrates consumption and methane production (Fernández-Rodríguez et al., 2013). However, thermophilic temperatures are more energy-intensive and can also result in the formation of ammonia in the biodigester which hinders bio-methane production, if not properly managed (Appels et al., 2008). Irrespective of the temperature employed, this needs to be kept constant within the digestion process. A sudden change in temperature may drastically decrease biogas production until the microorganisms are acclimated to the new operating temperature (Ward et al., 2008).

- **Hydraulic retention time**

Hydraulic retention time is defined as the average time the liquid substrate stays within the digester (Kothari et al., 2014). The hydraulic retention time is dependent on the substrates being digested and on the operating temperature. With highly biodegradable substrates such as food wastes, the hydraulic retention time is decreased while digesting wastes with high lignin content increases the hydraulic retention time. Likewise, thermophilic temperatures may reduce the hydraulic retention time due to increased rate of substrates consumption and degradation. Typically, the hydraulic retention time varies between 10 to 40 days (Kothari et al., 2014). The hydraulic retention time essentially determines the size of a biodigester. A higher retention time for a fixed flow rate implies a higher digester volume as opposed to a shorter retention time. However, too short retention time implies washout of methanogens, which eventually decreases biogas production (Appels et al., 2008; Panigrahi and Dubey, 2019).

- **C:N ratio**

The carbon:nitrogen (C:N) ratio gives an indication of the balance between carbon to nitrogen in the organic substrate to be digested so as to ensure optimum biogas production. A low C:N ratio may imply high nitrogen content or low carbon content. High nitrogen content results in the formation of ammonia gas in the digester which has an inhibitory effect on microbial activities and methane production (Kothari et al., 2014). Likewise, a low carbon content represents a low carbon source for the microorganisms to feed on (Khalid et al., 2011), resulting in a decreased microbial activity and low biogas production; on the other hand, a high C:N ratio may either imply a high carbon content or a low nitrogen content. Between a high carbon content and a low nitrogen content, the latter is more detrimental to biogas production. Microorganisms in the AD process require nitrogen as a nutrient while the synthesis of ammonium in the digestion process from nitrogen adds alkalinity to the system and this assists in preventing pH drop and process inhibition (Khalid et al., 2011). Optimum C:N ratios for effective AD and biogas production has been reported to be between 20:1 to 30:1 (Abbasi et al., 2012).

- **Organic loading rate**

Organic loading rate is the amount of organic matter (expressed as volatile solids (VS) or chemical oxygen demand) fed to a bioreactor per unit volume of the reactor (Kothari et al., 2014). With waste composition and characteristics varying throughout the year, it is important to ensure a constant feed to the bioreactor and this is ascertained through the organic loading rate. A constant loading rate ensures uniform or constant biogas production while a high organic loading rate (or shock loading to the bioreactor) may result in increased formation and accumulation of volatile fatty acids, drastic drop in pH, suppression of methanogenic activities and inhibition of bio-methane production (Kothari et al., 2014; Panigrahi and Dubey, 2019). Biogas plants handling organic fraction of municipal solid waste typically have organic loading rates varying from 4.4 to 22 g_{VS}/L/day (Panigrahi and Dubey, 2019).

2.1.3 Anaerobic treatment of OFMSW

The AD treatment of OFMSW can reduce the amount of solid waste sent to landfills hence increasing its lifetime. The process will generate energy-rich biogas that can be used to produce electricity for sale generating revenue to cover a portion of the cost to operate the facility and at the same time increasing the share of renewable energy which is one of the objectives of the energy policy. Furthermore, the digestate emanating from the process can further be composted to pasteurize and mineralize the biosolids for safe use as soil conditioner. Revenues can also be generated from the sale of compost to the farmers.

The viability of implementation of such project is mainly influenced by the biogas yield (or methane) of feedstock for subsequent electricity generation and the amount of compost that can be derived from the digested material. The project can also explore direct sale of biogas for cooking or upgrading to biomethane for use as transport fuel. The scope of this work is however limited to generation of biogas for electricity generation.

2.2 Identification, quantification and valorisation of by- products

Digestate is a mixture of microbial biomass and undigested material that is produced in huge amounts in addition to biogas. Digestate can be mechanically divided into liquid and solid fractions (depending on the process) and stored separately for ease of handling and transportation. The liquid fraction is composed of larger quantities of nitrogen and potassium, while the solid fraction contains residual fibres and phosphorus (amongst others). As a result, the use of digestate as a fertilizer or soil improver has sparked a lot of attention in recent decades (McDowell *et al.*, 2020). Its use in agriculture has both economic and environmental advantages, such as the ability to replace commercial fertilizers, which is crucial in the recycling of restricted nutrients like phosphorus. According to Walsh et al. (2012), liquid digestate, unlike commercial fertilizers, can maintain or boost grassland culture yields while also reducing nutrient losses to the environment.

Digestate has primarily been employed on an agricultural scale to improve soils. However, its ever-increasing output causes issues with transportation costs, greenhouse gas emissions during storage, and a high nitrogen concentration, limiting its use to only land application. As a result, research into alternate valorisation methods to lessen the environmental impacts of digestate and increase the economic profitability of AD plants is expected to gain traction in the future.

3 Quantification of Biogas and Energy Production Potential (Deliverable 3.1)

3.1 Determination of Methane Yields from Organic Solid Wastes

3.1.1 Molecular Formulae Derivation and Methane Yields Calculations

The simplistic model can be used to determine the methane yield of a substrate using its ultimate (elemental) analysis. Elemental analysis of the OFMSW was only done for the period January to December 2020, the approach that was taken to estimate methane yield can only allow methane determination for this period. Therefore, calculations were done for 2020 and the year will thus be used as a baseline in the subsequent deliverables.

Given that the data that is currently available is quantities and ultimate (elemental) analysis of the feedstock for the AD plant, a theoretical approach to estimate the biogas yield was taken. The model assumes that the biodegradation of the substrate fed to the digester goes to full completion. However, since this is not the case practically, the methane degradability and up-scaling extrapolation factor were considered, thereby giving a more realistic methane yield that is typically observed at full-scale applications.

The chemical equation (equation 1) for the reaction biochemical degradation of the substrate was derived by Buswell and Mueller (1952). However, the model excluded nitrogen and sulphur in the reaction, a modification which was made later by Boyle (equation 2) (Achinas and Euverink, 2016). The elemental analysis confirmed the presence of Carbon (C), Hydrogen (H), Oxygen (O) and Nitrogen (N), thus, equation 2 is more applicable than equation 1.

$$C_aH_bO_c + \left(a - \frac{b}{4} - \frac{c}{2}\right) H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4}\right) CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4}\right) CO_2 \tag{1}$$

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right) H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{d} - \frac{e}{4}\right) CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right) CO_2 + dNH_3 + eH_2S \tag{2}$$

The subscript a, b, c, d and e can be calculated as per the equation below:

$$a = \frac{ultimate\ elemental\ mass\ of\ C}{MM_C} \tag{3}$$

$$b = \frac{ultimate\ elemental\ mass\ of\ H}{MM_H} \tag{4}$$

$$c = \frac{ultimate\ elemental\ mass\ of\ O}{MM_O} \tag{5}$$

$$d = \frac{ultimate\ elemental\ mass\ of\ N}{MM_N} \tag{6}$$

$$e = \frac{ultimate\ elemental\ mass\ of\ S}{MM_S} \tag{7}$$

Where MM_C , MM_H , MM_O, MM_N and MM_S is the atomic weight of carbon, hydrogen, oxygen, nitrogen and sulphur, respectively.

The average composition of above-mentioned elements were computed for the OFMSW generated between January to December 2020 from elemental composition of the FW and YW (Appendix – Table A.1 and A.2). The calculated elemental composition was then used to derive the molecular formulae for which is representative of the food and yard waste generated on the island (table A.3).

The subscript **a**, **b**, **c** and **d** were determined by dividing the percentages of mass composition of the by the molecular weight of respective element in the first iteration. In the second iteration, the values of the subscripts were normalized against the lowest value obtained. Since the ultimate elemental analysis did not detect the sulphur element in both FW and YW, the value of e was assumed to be 0 and the sulphur element was dropped out in all the derivation of empirical formulae. The derived molecular formula was used to determine the theoretical biochemical methane potential (TBMP) for the substrates using equation 8.

$$TBMP\ (m^3 CH_4 \cdot tVS^{-1}) = \frac{22.4 \times (\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4})}{12.017a + 1.0079b + 15.999c + 14.0067d + 32.065e} \tag{8}$$

Practically, biochemical reaction represented in equation 2 does not reach 100% conversion, thus, the relation between the theoretical and experimental bio-methane potential (BMP) is methane biodegradability (MD) of that substrate.

$$MD = \frac{BMP}{TBMP} \times 100\% \tag{9}$$

Using the assumed MD, the expected experimental BMP was calculated. The MD of OFMSW was assumed to be 52.6%. The value is an average of the MD values obtained from the work of Nielfa, Cano & Fdz-Polanco (2015), Orangun *et al* (2021) , Elbeshbishy, Nakhla & Hafez (2012) and Jeon *et al* (2007). All the experiments were conducted under the mesophilic temperature regime.

The methane yield obtained in the laboratory are often different to those observed at full-scale operation. The extrapolation factor is thus used to estimate full-scale methane yield (FSMY) from the BMP experimental results. The extrapolation factor ranges from 80 to 90% (Holliger, Fruteau de Laclos & Hack, 2017). The up-scaling extrapolation factor of 85%, an average of the lower and upper bound of the range, was used in this study to determine the yield that can be expected to be observed at full-scale operation.

3.1.2 Methane Yields of OFMSW

Molecular formulae were derived for average elemental composition of FW and YW sampled monthly from MSW generated on the island in 2020. The molecular formulae for FW and YW are $C_{23}H_{59}O_{22}N$ and $C_{24}H_{54}O_{25}N$, respectively. The determined molecular formulae were then used in Boyle's chemical equation to determine the methane yields of the two wastes, the results of which are shown in table 1.

Table 1: Methane yields and biogas yields for OFMSW generated in different months

Type of Organic Waste	TBMP (m^3 CH_4/t VS)	BMP (m^3 CH_4 /t VS)	FSMY (m^3 CH_4/tonne VS)	FSMY (m^3 CH_4/tonne of waste)
Food Waste	414.9	218.4	185.6	81.5
Yard Waste	384.6	202.4	172.0	67.1

The FSMY is 86.3 and 71.1 m^3/tonne of food and yard waste, respectively. The methane yield obtained was compared with some of the yield obtained from literature for source sorted organic fraction of municipal solid waste (ms-OFMSW). Seruga and co-workers (2020) obtained an average methane yield of 65.5 CH_4/tonne (111.1 m^3 biogas/tonne) digesting of ss-OFMSW at full-scale under thermophilic temperature regimes. Rolewicz-Kalinska and co-workers (2016) surveyed several AD plants processing ss-OFMSW and obtained an average biogas yield of 60-90 m^3/tonne of ss-OFMSW), where Monson and co-workers (2007) obtained 70-110 m^3 biogas/tonne ms-OFMSW of the surveyed full-scale installations. The methane yield obtained in this work seems to be higher than that obtained in literature for full-scale digestion of ss-OFMSW.The figures for methane production might be slightly different at full-scale application. This is because the methane yields will change with the variability of composition, however, the yields determined in this work are within the range of that of AD system for OFMSW listed in the work of Ayodele and co-workers (2014). However, the BMP experiments will not be able to determine the effect of organic loading rate, accumulation of micronutrient and toxic/inhibitory substances over the long period of operation on the methane yields. As such, continuous fermentation will have to be conducted.

3.1.3 Methane Production from OFMSW

The 100 TPD plant will process mainly food waste, and it will supplemented by yard waste. The plant will run for 300 days and the other 65 days will reserved for shutdown, maintenance and start-up. As such, 30,000 tonnes per year (TPY) of organic waste will be required. The plant will be sited at one of the transfer station or landfill or a neighbouring region. FW will be the main component of AD and it will supplemented with YW. Collection efficiency of 85% for FW generated was assumed (Seruga *et al*, 2020). Of the total amount of FW handled at the various transfer station and landfill, only 85% is considered to be available for the AD plant, for the plant to have sufficient waste for 30,000 TPY, the FW will be supplemented by YW.

The obtained methane yields were used to calculate the expected daily methane production from 100 TPD AD plant,the variation of the biogas production at the various disposal sites are shown in Figure 3.

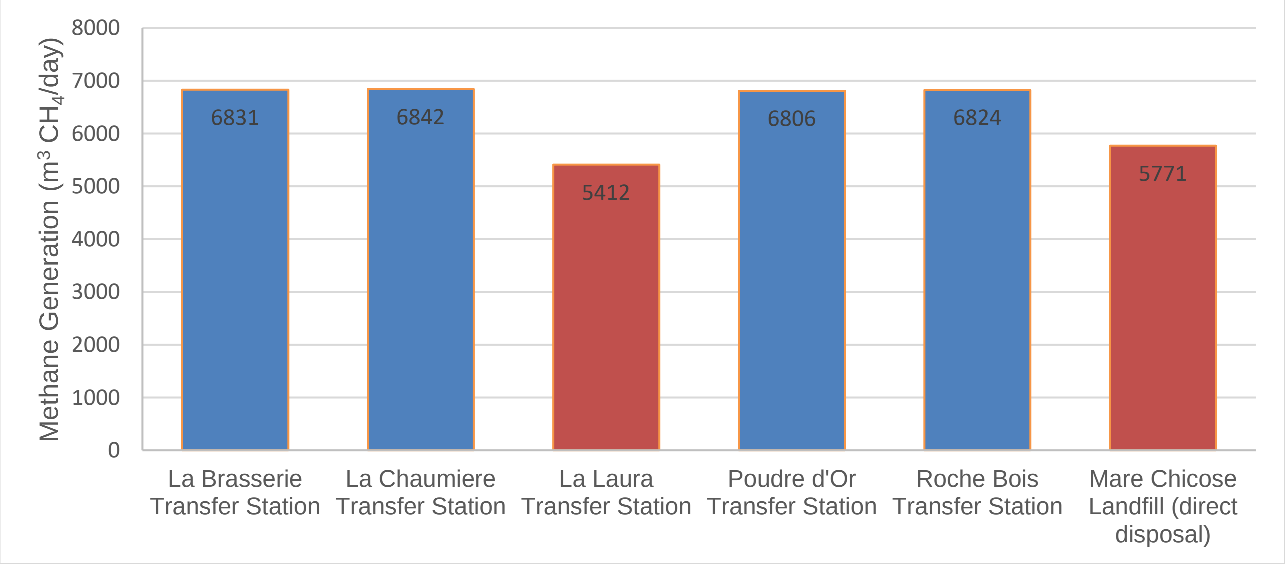


Figure 3: Methane production potentials at various waste handling facilities.

Methane production at the four transfer stations are comparable as seen in figure 3. The four transfer stations are La Basserie, La Chaumiere, Poudre d'Or and Roche Boise. La Chaumiere Transfer has a highest methane production as the transfer station handles more food waste than the other three transfer stations. The methane production at the four transfer stations ranges from 6806 to 6824 m^3 CH_4 /day. La Laura transfer station and Mare Chicose landfill receives less than 30,000 TPY of organic waste. As such, the methane generated at these two facilities are lowest in terms of methane generation capacity. If the AD plant is to be sited at La Laura, then the make up to reach 30,000 TPY will have to be catered by transporting food wastes from either Poudre d'Or transfer station or the Mare Chicose landfill (or their neighbouring regions) to the AD plant at La Laura. If the AD plant is to be sited at Mare Chicose, then the make up to reach 30,000 TPY will have to be catered by transporting food wastes from La Laura transfer station to the AD plant at Mare Chicose.

3.2 Energy Potential Estimation and Electrical Energy Production Potential

3.2.1 Energy Generation Calculations

The biogas that will be produced can be fed to the gas turbine for electricity generation and heat recovery. Using the amount of biogas (Q_{CH4}) determined in 3.1, estimation of the electricity (E_{el}) generation potential was calculated using equation 10 (Cesaro & Belgiorno, 2021). The methane energetic potential (E_{CH4}) was assumed to be 10 kW h/m^3 as per the work of Ariunbaatar and co-workers (2014) and electrical efficiency (η_e) of the plant was assumed at 32.5%, an average of the lower and upper bound of the electrical efficiency which ranges from 25 – 40% for gas turbine (Wellinger et al, 2013).

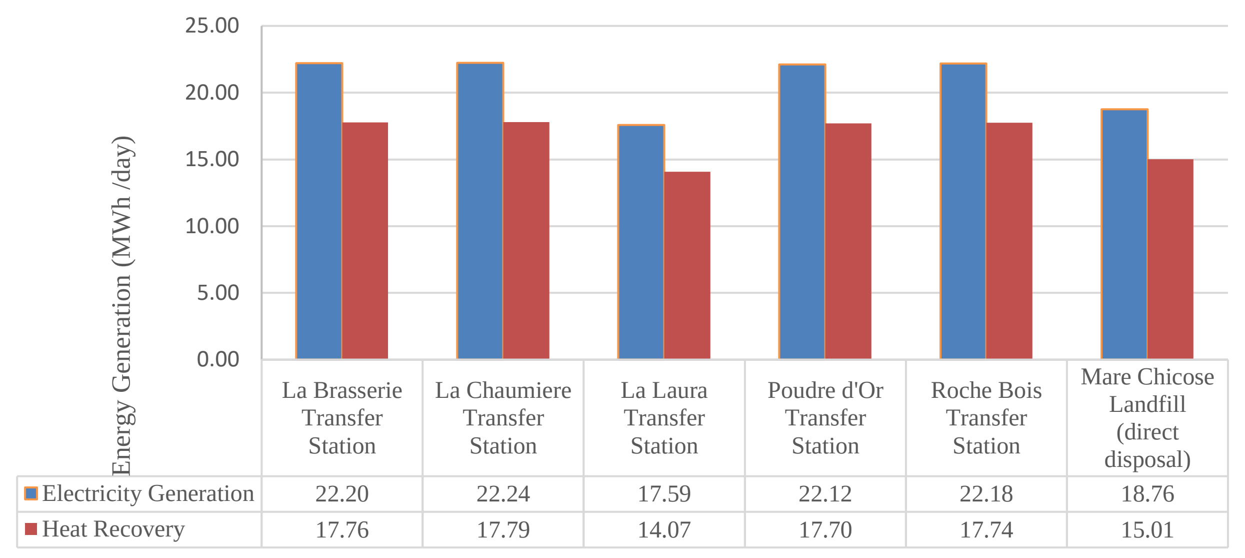
$$E_{el} = E_{CH4} \times Q_{CH4} \times \eta_e \tag{10}$$

The waste gas stream emanating from the CHP plant still have high energetic potential that may be recovered as thermal energy. The heat recovered can be used to produce heating water, steam or used directly waste stream gas. Heating water or steam can be used for temperature control in the digester, thermal drying of digestate and/or excess thermal energy might be used for various heating purposes off-site. Depending on the location of the plant, the demand for heating water, steam or waste gas heat might be another potential avenue for revenue generation. The heat recovery potential (E_{th}) was calculated using equation 11 Thermal energy recovery efficiency (η_{th}) was assumed at 40% , this an average of lower and upper bound of thermal recovery effiencies which ranges from 30 – 50% for gas turbine(Wellinger *et al*, 2013).

$$E_{th} = E_{CH4} \times Q_{CH4} \times \eta_{th} \tag{11}$$

3.2.2 Energy Generation from Methane produced from OFMSW

The biogas produced from AD of OFMSW can be used for electricity generation and heat recovery in the CHP engine. The electricity generation and heat recovery potential for various transfer stations are shown in Figure 4.



	La Brasserie Transfer Station	La Chaumiere Transfer Station	La Laura Transfer Station	Poudre d'Or Transfer Station	Roche Bois Transfer Station	Mare Chicose Landfill (direct disposal)
🟦 Electricity Generation	22.20	22.24	17.59	22.12	22.18	18.76
🟥 Heat Recovery	17.76	17.79	14.07	17.70	17.74	15.01

Figure 4: Electricity and heat generation potential at various waste handling facilities.

The electricity and thermal generation are dependent on the methane production. Consequently, the trend for electricity and thermal generation is similar to that observed for methane production in Figure 3. The electricity and heat generation is comparable for the four transfer stations with generation of about 22 and 18 MWh/day, respectively. The highest electricity and heat generation can be realized at the La Chaumiere transfer station. Because of the lower methane production at La Laura Transfer Station and the Mare Chicose Landfill, the electricity and heat generated at these two facilities are lowest compared to the other transfer stations.

4 Identification, quantification and valorisation of by-products (Deliverable 3.2)

4.1 Identification and quantification of compost and liquid fertiliser production potential from digestate

The proper disposal of the digestates produced is critical to the long-term viability of biogas producing systems. The main characteristics of the historical data of solid organic wastes from Mauritius were identified as fresh produced markets (leaves from vegetables and fruits and rotten vegetables and fruits), hospitality (food wastes and yard wastes from hotels) and domestic sector (food wastes and yard wastes). The identified highest contributor to solid organic waste can be compared with quality standards to access their potential use as fertilisers. For the digestates to have a high fertilising potential, their contents of NH_4-N must be high, however, their application in agriculture might be restricted by their Cu and Zn contents, salinity, biodegradability, phytotoxicity and hygiene characteristics, that must be addressed to obtain the maximum benefits.

Digestate NH_4^+-N content is directly related to the initial Total Kjedahl Nitrogen (TKN) content in the feedstock. TKN is largely converted to soluble inorganic nitrogen, such as ammonium (NH_4^+) and its equilibrium companion ammonia (NH_3), during AD. Their steady-state balance (pKa~9.25 at 25°C) is primarily determined by the temperature and pH of the digestate: the higher the pH (>12) and temperature, the greater the fraction of free ammonia. Moreover, NH_4^+-N+ is also used by anaerobic microorganisms for growth. Digestates have higher NNH_4^+ / TKN ratios than feedstock. Digestates from highly degradable feedstocks such as poultry and pig manure are characterized by high N-NH_4^+ / TKN ratios and narrow C:N ratios, while lignocellulosic feedstocks such as sorghum and maize silage that are low in N lead to a low N-NH_4^+ / TKN ratio in digestate (Möller & Müller, 2012). These parameters indicate whether pre- or post-treatments are required to improve digestate quality to acceptable levels. As a result, when controlling the digestion process, including substrate selection, digestate quality must be considered in order to employ digestates as fertilisers without incurring the additional cost of post-digestion conditioning treatments.

Composting is an aerobic process in which microorganisms present in organic material degrade organic matter. Composting produces mainly CO_2, water, minerals, and biologically stabilized material. Open (e.g. windrow, static pile, mattress), contained (e.g. channel and cell, aerated pile), or reactor (e.g. tunnel, revolving drum) technologies are used to produce compost in central facilities. YW, FW, sludge, and manure are the most typical waste fractions composted, and most often a blend of these fractions is used. Organic waste in the municipal waste stream consists mainly of YW and FW. For Mauritius, a central composting facility as treatment option is recommended as compared to home composting. One of the most notable distinctions between central and home composting is the lower waste additions and lower temperatures for home composting, whereas temperature development during central composting climbs dramatically and is frequently beyond

70°C. This is because as easily degradable organic matter is digested, microbial activity and temperature decrease.

The complete quantification of compost will be discussed in detail in Output 5 in the mass balance. The mass balance includes total organic matter, carbon, nitrogen and phosphorus. The compost refuse including dust (from the compost refining process) and final compost are identified as output materials.

This section contains a list of common assays that can be used to determine the quality of compost which can be used to match compost to a specific use in Mauritian context, once the compost facility is implemented.

- Organic matter

In many cases, organic matter is the most important component of compost for improving soil quality. Total organic carbon and organic matter are expressed as a percentage of compost dry weight. Mineral soil (poor in organic matter) can be combined into compost as feedstocks or by turning on bare ground, resulting in low organic matter values in compost. When only organic waste streams are used, the stabilized compost product contains a high amount of organic matter. A high level of organic matter, on the other hand, may indicate an incomplete composting process or unstable compost. Following application, this organic matter will be partially respired by microbial breakdown.

- pH

Compost pH ranges from 6 to 9.5, with lower values for plant-based composts and higher values for manure-based composts. The majority of plant-based composts are acidic (pH 6) to alkaline (pH 6) in nature (pH 7.5). A pH of 7 to 8 is typical for manure-based composts. Most manure-based composts have a pH that renders acid-loving plants like rhododendron and blueberry unsuitable.

- Electrical conductivity (EC)

The total salt content of the compost is determined using electrical conductivity (EC). Salt stress can be caused by excessive salt content (> 1500 µS/cm), especially when compost is employed as a growth medium. Plants may be harmed by high salt levels, with seedlings and transplants being the most vulnerable. Salts are frequently transferred downhill by leaching after compost application. When irrigation water transfers soluble salts over a planting bed, as it does with drip irrigation, salt concentrations can build up, increasing the risk of plant harm. The compost application rate, soil EC previous to application, compost integration depth (tillage), soil texture, and irrigation water management all influence the acceptable EC for compost in field circumstances.

Table 2 shows nutrient interpretations based on a database of samples from the Compost Analysis Proficiency Program of the United States Composting Council (U.S. Composting Council, 2001b).

These standard ranges can be used as a guideline for purchasing bulk compost and as a starting point for inquiries to be asked of the compost processor.

Table 2: Typical compost nutrient interpretations based on total nutrient analyses (U.S. Composting Council, 2001).

Nutrient	Standard range (% of dry weight)	Comment
Nitrogen (N)	1–2	If the total N content of compost is less than 1 percent, consider supplemental N fertilization after compost application. Composts with 1 to 2 percent N have minimal effect on N fertilizer requirements for crop production. If total N exceeds 2 percent, the compost can replace a portion of typical N fertilizer input for crop production. See the sidebar "Interpreting compost nitrogen analyses" (page 5) for more information.
Phosphorus (P)	0.3–0.9	If P exceeds 0.7 percent, the compost feedstocks likely included manure. If P content is below 0.3 percent, consider supplemental P fertilizer application if a soil test indicates need.
Potassium (K)	0.5–1.5	If K exceeds 1.5 percent, the compost feedstocks likely included manure, food waste, or grass clippings. Compost K is considered equivalent to fertilizer K as a source of K for plants.
Calcium (Ca)	1.5–3.5	If Ca exceeds 4 percent, the compost feedstocks may have included soil, gypsum, or lime

Magnesium (Mg)	0.25–0.7	If Mg exceeds 0.75 percent and K is less than 1.5 percent, an imbalance in the ratio of Mg to K may impact plant growth.
Sodium (Na)	below 0.6	If Na exceeds 0.6 percent, compost may injure plants.
Sulfur (S)	0.25–0.8	If S is less than 0.25 percent, plant S deficiency is possible; consider supplemental S fertilization. If S exceeds 0.8 percent, it is likely that gypsum was added to the feedstocks.

However, apart from the classical farmland application as fertilizer or soil amendment, valorisation routes for the utilization of digestate has emerged. This is due to the limitations resulting from the sole use of digestate as fertilizer and soil amendments. Furthermore, the predicted future increase in digestate generation necessitates the development of alternate pathways. The next section will outline some unique prospects for digestate use identified for the Mauritian market.

4.2 Analysis of the valorisation and usage potential of the compost and liquid fertiliser produced on the Mauritian market

This section provides a brief description of the potential usage of the composts and liquid fertilisers and also alternative routes of digestate, other than land applications, including: the use of the digestate liquor for replacing freshwater and nutrients in algae cultivation and conversion of digestate into high added value compounds such as pyrochar, activated carbons, etc. All limitations related to potential use of compost and liquid fertilisers produced from digestate are aimed at ensuring a more secure and economically sustainable exploitation of digestate. The simplest approach would be to recover nutrients (N, P, and K), usually in the form of high-quality, nutrient-rich concentrates that could be sold. Composting, drying, evaporation, stripping, precipitation, membrane separation, and concentration are technologies that can be used.

The liquid digestate can be used for algae growth. The combination of algae growth with AD was first proposed in the 1950s by Golueke et al. (1957), who claimed that this technique would allow sunlight to be converted into chemical energy. This concept, however, remained dormant until lately. Several investigations have been carried out in recent years with the goal of proving the viability of employing liquid digestates from various sources as a nutrient source in microalgal production. The need for alternate feedstocks to reduce the impact of first-generation biofuels (i.e., those made from edible crops) production on the food commodity market has sparked interest in microalgal cultivation. According to published studies, algal cultivation for biofuel production is still far from economically viable because production/extraction costs are still prohibitively high (Adeniyi, Azimov & Burluka, 2018, Richardson et al, 2014). Among the various cost-cutting strategies, nutrient recovery from waste streams appears to be the most promising and possibly unavoidable.

Another promising alternative route to valorizing both solid and liquid digestates is bioethanol production via biological fermentation. Solid digestate has recently attracted interest for bioethanol production due to its high cellulose fibre content. However, digested fibres may contain physicochemical barriers such as lignin. This has the potential to limit carbohydrate availability and degradation. To overcome these natural barriers, a treatment step should be performed prior to enzymatic hydrolysis and fermentation. Dilute-alkali treatments are commonly used to solubilize lignin from the lignocellulosic matrix and increase the cellulose content of the remaining solid fraction. In general, it has been demonstrated that digestate produced by the AD process has several advantages for bioethanol production, owing to the fact that the digestate obtained is generally rich in cellulose, which is easily accessible.

A value-added component soil amendment based on pyrochar can also be potential for the market. Pyrochar is a charcoal-like residue produced during the pyrolysis process. Pyrochar production has recently come to the forefront of climate change mitigation efforts around the world, as it has the potential to play a significant role in sequestering atmospheric carbon dioxide. Indeed, converting biomass into pyrochar can help stabilize the carbon captured by plants in the form of charcoal, which is highly resistant to biological degradation. Pyrochars have also attracted attention as soil improvers due to their physicochemical properties, in order to preserve the fragile quality of soils; this practice is consistent with the principles of ecology and sustainable agriculture. Because pyrochars are extremely porous, they have a large surface area and porosity available for adsorption or chemical reaction, as well as a high exchange capacity. Pyrochars, due to their high accessible surface area and porosity, they can improve soil water-holding capacity and alleviate drought stress in water scarce countries like South Africa. Their porous structure should act as a haven for beneficial soil microorganisms such as micorrhizae and bacteria. Furthermore, they have the potential to interfere with the binding of important nutritive cations and anions.

5 Conclusion

There is an increasing global concern on the disposal of solid waste, this is because unsafe disposal of such waste has negative impact on health of humans and animal, release of greenhouse gas from organic fraction of waste further contributes to climate change, and leachate from such waste contains toxic contaminant and pathogens that can pollute both surface and groundwater. For the Mauritian government, the problem is further exacerbated by limited land mass for landfills, which is a cheaper method of disposal of waste. This study seeks to determine the viability of implementation of AD of OFMSW in Mauritius. The project will comprise the production of biogas from OFMSW for electricity generation and the production of any valuable products i.e. liquid/solid fertilizers.

In this work, estimations were made for methane production and subsequent electricity and heat generation for a 100 TPD AD plant for digestion of FW supplemented with YW, and production of valuable by-products thereof. Estimations were made for plant that can be implemented and process the waste received at the various transfer stations and landfill. The daily methane production at the four transfer stations ranged between 6806 – 6824 m^3 CH_4/day. La Laura and Mare Chicose Landfill does not handle sufficient OFMSW for a 100 TPD AD plant. As such, FW will have to be transported from neighbouring disposal sites to make up the 100 TPD capacity, if a future biogas plant is sited at either La Laura transfer station or the Mare Chicose landfill. As regards energy production, about 18-22 and 14-18 MWh/day of electricity and heat respectively can be generated at the various disposal sites in Mauritius.

6 Recommendations

Several assumptions have been made in this study to estimate the methane yields of OFMSW and these calculations have given figures that are close to the true value. However, the following recommendations are made for accurate measurement of yield:

- BMP experiments for determination of actual yields and methane degradability, so to account for the synergistic/antagonistic effect of co-digestion to two substrates.
- A factor of 0.85 have been used to extrapolate the methane yield at full-scale from the estimated BMP figures, however, BMP does not account for the effect of organic loading rate, and accumulation of toxic/inhibitory elements/compounds in the digester. For accurate extrapolation factor measurement, continuous fermentation test may need to be conducted.

7 References

Achinas, S. and Euverink, G., 2016. Theoretical analysis of biogas potential prediction from agricultural waste. *Resource-Efficient Technologies*, 2(3), pp.143-147.

Achinas, S. and Euverink, G., 2016. Theoretical analysis of biogas potential prediction from agricultural waste. *Resource-Efficient Technologies*, 2(3), pp.143-147.

Adeniyi, O.M., Azimov, U. and Burluka, A., 2018. Algae biofuel: current status and future applications. *Renewable and sustainable energy reviews*, *90*, pp.316-335.

Al Mamun, M. R. (2015). Possibility of Anaerobic Co-digestion of Cafeteria, Vegetable and Fruit Wastes for Biogas Production without Inoculum Source. *International Journal of Renewable Energy and Environmental Engineering*. 3. 219-225.

Ariunbaatar, J., Panico, A., Frunzo, L., Esposito, G., Lens, P. and Pirozzi, F., 2014. Enhanced anaerobic digestion of food waste by thermal and ozonation pretreatment methods. *Journal of Environmental Management*, 146, pp.142-149.

Ayodele, T., Ogunjuyigbe, A. and Alao, M., 2018. Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria. *Journal of Cleaner Production*, 203, pp.718-735.

Brown, D. and Li, Y., 2013. Solid state anaerobic co-digestion of yard waste and food waste for biogas production. *Bioresource Technology*, 127, pp.275-280.

Buswell, A. and Mueller, H., 1952. Mechanism of Methane Fermentation. *Industrial & Engineering Chemistry*, 44(3), pp.550-552.

Cesaro, A. and Belgiorno, V., 2021. Anaerobic digestion of mechanically sorted organic waste: The influence of storage time on the energetic potential. *Sustainable Chemistry and Pharmacy*, 20, p.100373.

Elbeshbishy, E., Nakhla, G. and Hafez, H., 2012. Biochemical methane potential (BMP) of food waste and primary sludge: Influence of inoculum pre-incubation and inoculum source. *Bioresource Technology*, 110, pp.18-25.

Fei, F., Wen, Z., Huang, S. and Clerq, D. D. (2018) Mechanical biological treatment of municipal solid waste: Energy effiency, environmental impact and economic feasibility analysis. *Journal of Cleaner Productions, 178.* pp. 731-739.

Feng, L., Li, Y., Chen, C., Liu, X., Xiao, X., Ma, X., Zhang, R., He, Y. and Liu, G., 2013. Biochemical Methane Potential (BMP) of Vinegar Residue and the Influence of Feed to Inoculum Ratios on Biogas Production. *BioResources*, 8(2).

Golueke, C.G. and Oswald, W.J., 1959. Biological conversion of light energy to the chemical energy of methane. *Applied microbiology*, *7*(4), pp.219-227.

Holliger, C., Fruteau de Laclos, H. and Hack, G., 2017. Methane Production of Full-Scale Anaerobic Digestion Plants Calculated from Substrate's Biomethane Potentials Compares Well with the One Measured On-Site. *Frontiers in Energy Research*, 5.

Hoornweg, D. and Bhada-Tata, P., 2012. What a waste: a global review of solid waste management.

Jeon, E.J., Bae, S.J., Lee, D.H., Seo, D.C., Chun, S.K., Lee, N.H. and Kim, J.Y., 2007, October. Methane generation potential and biodegradability of MSW components. In *Sardinia 2007 eleventh international waste management and landfill symposium*.

McDowell, D., Dick, J.T., Eagling, L., Julius, M., Sheldrake, G.N., Theodoridou, K. and Walsh, P.J., 2020. Recycling nutrients from anaerobic digestates for the cultivation of Phaeodactylum tricornutum: A feasibility study. *Algal Research*, *48*, p.101893.

Möller, K. and Müller, T., 2012. Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. *Engineering in Life Sciences*, *12*(3), pp.242-257.

Orangun, A., Kaur, H. and Kommalapati, R., 2021. Batch Anaerobic Co-Digestion and Biochemical Methane Potential Analysis of Goat Manure and Food Waste. *Energies*, 14(7), p.1952.

Rea, J., 2014. Kinetic Modeling and experimentation of anaerobic digestion (Doctoral dissertation, Massachusetts Institute of Technology).

Richardson, J.W., Johnson, M.D., Zhang, X., Zemke, P., Chen, W. and Hu, Q., 2014. A financial assessment of two alternative cultivation systems and their contributions to algae biofuel economic viability. *Algal Research*, *4*, pp.96-104.

Seruga, P., Krzywonos, M., Seruga, A., Niedźwiecki, Ł., Pawlak-Kruczek, H. and Urbanowska, A., 2020. Anaerobic Digestion Performance: Separate Collected vs. Mechanical Segregated Organic Fractions of Municipal Solid Waste as Feedstock. *Energies*, 13(15), p.3768.

U.S. Composting Council. 2001. Composting testing programs. https://compostingcouncil.org /programs/ (verified 03 Oct 2021).

University of Mauritius (UoM) & Council for Scientific and Industrial Research(CSIR). 2021. Status quo and baseline analysis of organic waste. Output 2.

Walsh, J.J., Jones, D.L., Edwards-Jones, G. and Williams, A.P., 2012. Replacing inorganic fertilizer with anaerobic digestate may maintain agricultural productivity at less environmental cost. *Journal of Plant Nutrition and Soil Science*, *175*(6), pp.840-845.

Rolewicz-Kalińska, A., Oniszk-Popławska, A., Wesołowska, J. and Ryńska, E., 2016. Conditions for the development of anaerobic digestion technologies using the organic fraction of municipal solid waste: perspectives for Poland. *Environment, Development and Sustainability*, 18(5), pp.1279-1296

Wellinger, A, Murphy, JP, Baxter, D, & Braun, R (eds) 2013, The Biogas Handbook : Science, Production and Applications, Elsevier Science & Technology, Cambridge. Available from: ProQuest Ebook Central. [16 August 2021]. p. 412

Appendix

Table A1: Total, volatile solids and elemental composition of FW generated in Mauritius (adapted from UoM & CSIR, 2021)

Months	TS (%)	VS(%)	C (%)	H (%)	O (%)	N (%)
Jan 20	40.08	94.85	43.382	8.603	45.888	2.127
Feb 20	50.23	95.02	38.858	7.969	51.537	1.635
Mar 20	44.90	93.53	39.140	8.905	49.750	2.205
Apr 20	48.40	94.98	41.270	9.052	47.738	1.940
May 20	53.21	95.62	37.980	8.156	51.804	2.060
Jun 20	30.71	93.18	39.938	8.430	49.582	2.049
Jul 20	54.41	96.89	37.758	8.845	51.419	1.978
Aug 20	49.86	96.01	39.457	8.924	49.602	2.018
Sep 20	41.68	96.24	39.190	8.314	50.461	2.035
Oct 20	60.47	86.35	38.700	9.091	50.196	2.012
Nov 20	37.46	93.21	36.491	8.270	53.272	1.966
Dec 20	47.25	95.94	39.233	9.325	49.160	2.282
Average	46.56	94.32	39.283	8.657	50.034	2.026

Table A2: Total, volatile solids and elemental composition of YW generated in Mauritius (adapted from UoM & CSIR, 2021)

Months	TS (%)	VS(%)	C (%)	H (%)	O (%)	N
Jan 20	38.03	88.14	41.800	6.957	49.216	2.026
Feb 20	30.85	85.16	39.290	7.873	50.636	2.201
Mar 20	42.02	86.91	37.620	6.880	53.990	1.510
Apr 20	27.13	88.53	41.090	7.320	50.000	1.590
May 20	39.75	88.18	38.910	6.610	52.810	1.670
Jun 20	41.01	91.96	35.386	6.943	54.819	2.852
Jul 20	61.59	83.27	41.564	8.040	48.769	1.627
Aug 20	59.05	88.35	37.865	7.401	52.810	1.924
Sep 20	39.09	88.57	39.746	7.585	50.919	1.751
Oct 20	56.94	89.15	38.363	6.926	52.836	1.875
Nov 20	53.15	83.06	39.464	8.297	50.474	1.765
Dec 20	47.45	87.07	25.799	5.786	66.801	1.614
Average	44.672	87.363	38.075	7.218	52.840	1.867

Table A.3: Molecular formulars of FW and YW collected in 2020 (Author’s calculation).

		C(a)	H(b)	O(c)	N(d)
	Molar Mass (kg mol)	12.01	1.01	16	14.01
Food Waste	Number of moles	3.2709	8.5713	3.1271	0.1446
	Subscript (a,b,c,d)	23	59	22	1
Yard Waste	Number of moles	3.1703	7.1467	3.3025	0.1333
	Subscript (a,b,c,d)	24	54	25	1

Table A.4: Methane degradability from various sources.

	Methane Dedradaibility (%)	**Citation**
	41	Elbeshbishy, Nakhla & Hafez, 2012
	49	Elbeshbishy, Nakhla & Hafez, 2013
	27	Elbeshbishy, Nakhla & Hafez, 2014
	63	Elbeshbishy, Nakhla & Hafez, 2015
	59	Elbeshbishy, Nakhla & Hafez, 2016
	87	Elbeshbishy, Nakhla & Hafez, 2017
	68.2	Jeon et al(2007)
	58.6	Jeon et al(2007)
	40	Nielfa, Cano & Fdz-Polanco (2015)
	33.5	
Average	52.6	

Table A.5: Methane production, electricity and heat generation at various waste handling facilities (Author's calculation).

Months	**Food Waste (tonnes/ year)**	**Yard Wate (tonnes/ year)**	**Least Amount of Food collected (tonnes/year)**	**OFMSW (tonnes/ year)**	**daily CH4 production (m^3/day)**	**Daily Electricity Generation (MWh/ day)**	**Heat Generation (MWh/day)**
La Brasserie Transfer Station	16463.60	23055.2	39518.8	6831	22.20	17.76	16463.60
La Chaumiere Transfer Station	17942.50	35117.3	53059.8	6842	22.24	17.79	17942.50
La Laura Transfer Station	9473.70	12683.1	22156.8	5412	17.59	14.07	9473.70
Poudre d'Or Transfer Station	12882.70	22223.2	35105.9	6806	22.12	17.70	12882.70
Roche Bois Transfer Station	15426.00	29074.0	44500.0	6824	22.18	17.74	15426.00
Mare Chicose Landfill (direct disposal)	8564.90	15391.3	23956.2	5771	18.76	15.01	8564.90