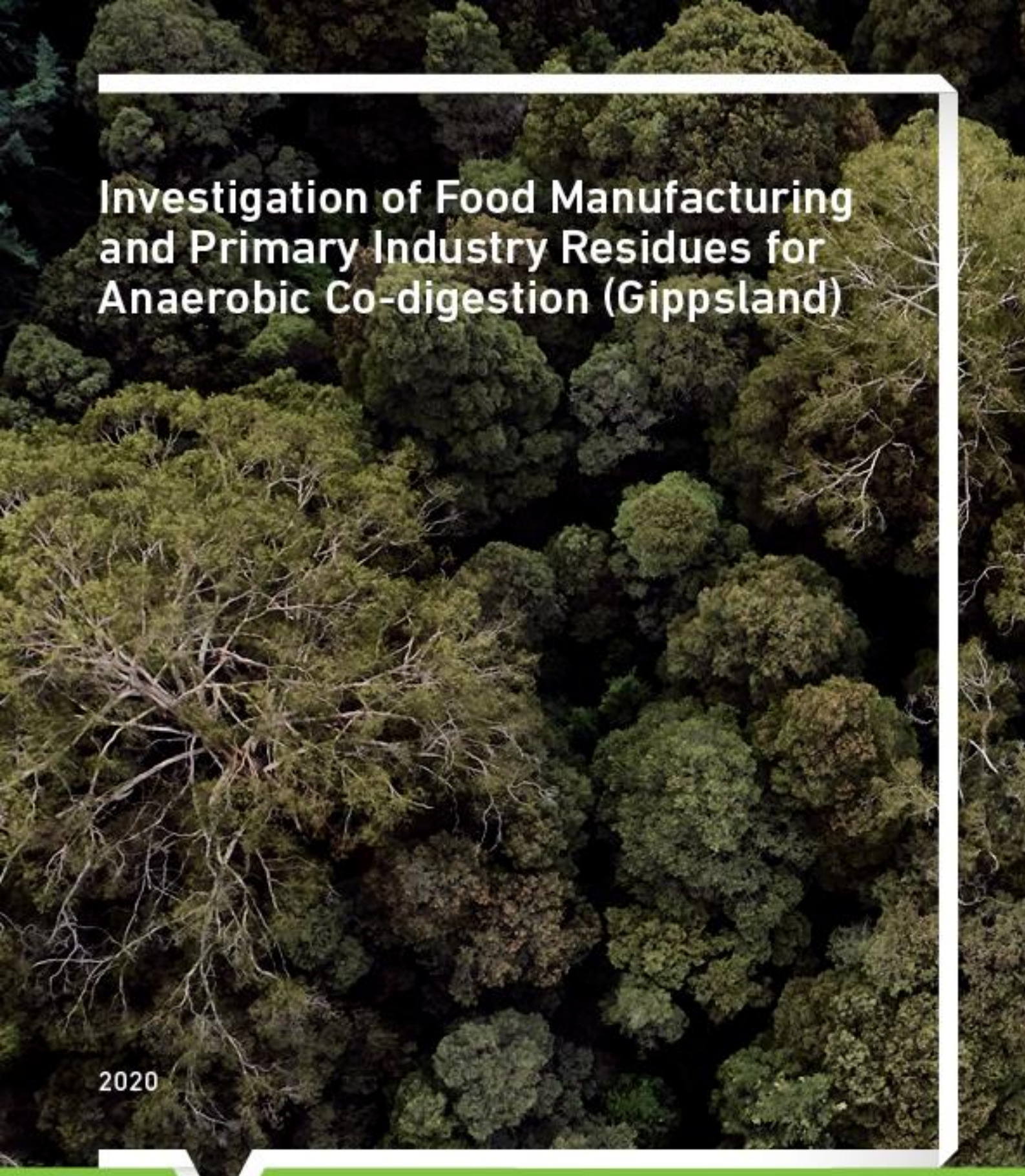

Investigation of Food Manufacturing and Primary Industry Residues for Anaerobic Co-digestion (Gippsland)

2020

Sustainability Victoria

VICTORIA State Government

Investigation of Food Manufacturing and Primary Industry Residues for Anaerobic Co-digestion (Gippsland) 2020

Prepared by Royal Melbourne Institute of Technology
RMIT University,
124 La Trobe St, Melbourne
Victoria 3000 Australia

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Acronyms and abbreviations

ABS	Australian Bureau of Statistics
ACoD	Anaerobic co-digestion
AD	Anaerobic digestion
BMP	Biochemical methane potential
C	Carbon
CH_4	Methane
COD	Chemical oxygen demand
CODs	Chemical oxygen demand soluble
C/N	Carbon to nitrogen [ratio]
CO_2	Carbon dioxide
DAF	Dissolved air floatation
EfW	Energy from waste
FAN	Free ammonia nitrogen
N	Nitrogen
NH_4	Ammonium
O	Oxygen
TAN	Total ammonia nitrogen
TN	Total nitrogen
TP	Total phosphorous
TS	Total solids
VA	Volatile acid
VFA	Volatile fatty acid
VS	Volatile solids

Executive Summary

This study was funded by Sustainability Victoria as part of its Australian Biomass for Bioenergy Assessment (ABBA) program supported by the Australian Renewable Energy Agency (ARENA). The focus of ABBA and the ARENA funding is to: provide reliable resource evaluation information on biomass feedstocks for bioenergy which remains a significant roadblock to the development of bioenergy projects across Australia. The study is a collaboration between C-Loop, a commercially and sustainability focussed agribusiness start-up and RMIT which has the laboratory facilities to reliably test organic residues for biogas and nutrient yields.

Victoria generates a variety of organic waste streams and waste substrates that will increase as the population grows. In 2015–16, 887,000 tonnes of organic matter were sent to landfill. With Victoria's population projected to increase by roughly 13% by 2025, if organic waste production keeps pace with growth and no new measures to divert organics from landfill are implemented, over a million tonnes per year will be sent to landfill. This also represents a major loss of a valuable nutrient resources, a resource that could replace its fossil-fuel based equivalent.[1]

The basis for testing organic waste arisings in the Gippsland area recognises that primary industry and food manufacturing are complementary in the region being within reasonable geographic proximity. The waste materials which have been sourced for testing are representative of not only Gippsland but northern (Goulburn Valley) and western (Western District) regions of Victoria, where dairy, beef, poultry and broadacre cropping are common farming practices, complemented by centralised food manufacturing facilities.

The biomass substrates testing regime in Gippsland focused upon non-recoverable food waste streams generated from a range of manufacturing facilities, supermarkets that are currently selling private label products and agriculture businesses where interest in alternative treatment opportunities to deal with these types of waste are gaining ground. The organics waste streams were selected due to their volume and proximity to one another in the regions, the testing regime is a strategic component of developing sustainable biomass supply chains. Biomass feedstock samples were selected on this basis and the results of benchtop anaerobic digestion (AD) testing form the substance of this report.

Samples were characterised for a range of physical and chemical parameters including total solids (TS), volatile solids (VS), total nitrogen, total phosphorus, ammonia (NH_4), chemical oxygen demand (COD),

[1] The manufacture of synthetic fertilisers for crop production is greenhouse intensive, contributing 1.2% to global emissions: A. Cowie (2004) *A Review of Greenhouse Gas Emission Factors for Fertiliser Production*, NSW Primary Industries.

pH, volatile acids (VAs) and carbon/ nitrogen ratio (C/N). These substrates are available in varying degrees depending on their generation, which can be seasonal or year-round.

Anaerobic digestion is a process in which anaerobic microorganisms break down organic matter to produce biogas. Optimal Anaerobic co-digestion (ACoD) aims to enhance biogas yield by C/N ratio optimisation while minimising the risk of inhibition due to ammonia and VA accumulation.

The potential of these substrates for biogas production was determined according to the biochemical methane potential (BMP) test. Batch BMP tests were carried out at mesophilic anaerobic conditions (37°C) and solids concentrations of 2%TS and 4%TS (i.e. 98% and 96% water content, respectively), typical of AD conditions. The results showed that higher biogas yields were obtained under the conditions of 2% TS. The maximum biogas yield of 1226.7 m^3/ton VS was obtained from thickened concentrate from food waste. Food wastes from supermarkets and thickened wastes from food processing factories generated biogas yields of 1049.8–1136.9 m^3/ton VS.

Anaerobic co-digestion, using multiple substrates, was shown to improve biogas yield. To determine the potential to enhance biogas production, a batch BMP test was carried out, taking into consideration the location of the available waste streams, yield, and key operating parameters such as C/N ratio and TS and VS content. Seven design systems were evaluated under mesophilic anaerobic conditions using 2-3 of the available substrates. Biogas production from ACoD batch experiments ranged from 407.9 ± 47.4 to 858.5 ± 121 m^3/ton VS.

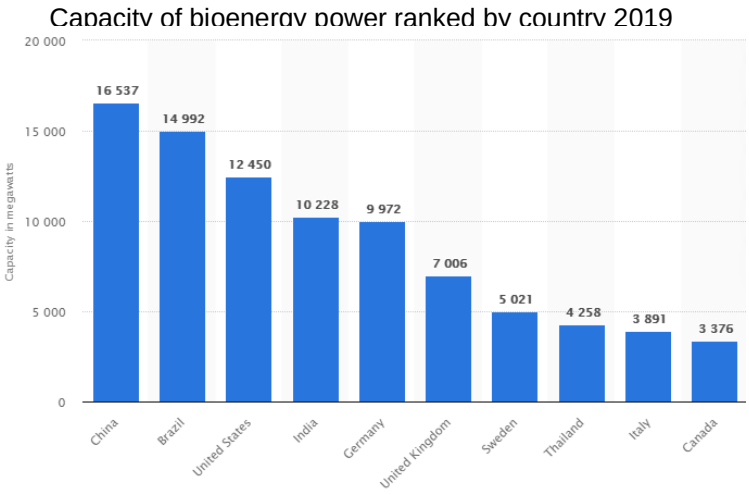
Audience

This report is intended for people interested in bioenergy project development and development of the industry more broadly. Intended audience could include primary producers and other biomass producers, the investment and finance sector, local and state government officials, industries that stand to benefit (particularly large heat users) as well as bioenergy project developers. Conversion of biomass and other organic waste arisings is fundamental to transitioning towards a circular, low-carbon economy and is common practice in many countries. Although bioenergy is relatively nascent in Victoria, the state has many bioenergy facilities fuelled by wood waste, milling residues, animal effluent and primary and secondary production residues. [2] This report presents the results of benchtop biogas yields from selected food wastes and biomass residues found throughout many regions of Victoria.

[2] Although there are in upwards of 30 bioenergy facilities across the state, there is potential for development of hundreds more.

Introduction

Victoria's population is expected to increase by 60 –130% between 2018 and 2066 – the fastest of all Australian states and territories (ABS, 2018). By 2027, the population of Victoria is expected to reach 7.5–7.9 million people (ABS, 2018). As the population grows, so will the amount of waste it generates. Between 2015–16 and 2016–17, the amount of kerbside garbage collected in Victoria increased by 4% (86,000 tonnes) to 2.23 million tonnes; of this waste, 463,000 tonnes (21%) was organic (Sustainability Victoria, 2018). Victorian industry and residential streams together sent 887,000 tonnes of food organics to landfill in 2015–16 (ABS, 2018).



Bioenergy has proved successful in Brazil, China, India, Thailand, the United Kingdom, the United States and throughout much of Europe but continues to be under-represented here in Victoria.[3] Anaerobic digestion (AD) is a well-developed and commercial technology with vast potential in Victoria courtesy of the availability of a wide variety of organic substrates. AD is a process in which microorganisms biodegrade organic matter to produce biogas (mostly methane) available as a source of energy, and digestate that can be used in various applications, including soil conditioning substituting fossil-based inorganic fertilisers. AD has advantages over other bioenergy technologies in its ability to process substrates with varying characteristics, including impurities and high moisture content (Xu et al., 2018). AD is a commercially proven and extensively demonstrated low emissions, circular economy solution.

Victoria leads Australia in agricultural production due to its mostly temperate climate, relatively high soil quality and stable water supply. In 2017, there were 29,661 agricultural operations in the state (Agriculture Victoria, 2018), producing a range of biomass waste streams suitable for AD. Similarly, industrial processes such as food processing and wastewater treatment in Victoria generate various substrates which have potential for use in bioenergy projects.

This research investigated the potential of substrates available in Victoria for use in AD or ACoD. By determining the suitability of substrates and their potential to produce biogas, this work identified lucrative waste streams that can be used in AD or ACoD, with simultaneous recycling of many desirable nutrients for agricultural use.

[3] Statista (cited Oct 2020) https://www.statista.com/statistics/476416/global-capacity-of-bioenergy-in-selected-countries/

Anaerobic Digestion

Anaerobic digestion breaks organic matter down into useful constituents, notably biogas, and is thus an efficient means of reducing the disposal of organic waste to landfill or other low value practices. Biogas is typically composed of 60–70% methane (CH_4), 30–40% carbon dioxide (CO_2) and smaller proportions of nitrogen (0–10%), H_2S (0–3%) and hydrogen. Biogas composition is dependent on several parameters, including digestibility of organic matter, feedstock composition, digestion kinetics, digester retention time and temperature. The AD process has four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Figure 1). Carbon, nitrogen and oxygen (C, N and O) are the main components of the organic waste that feature in digestion. The AD process is dependent on the interactions between diverse microorganisms in these four stages.

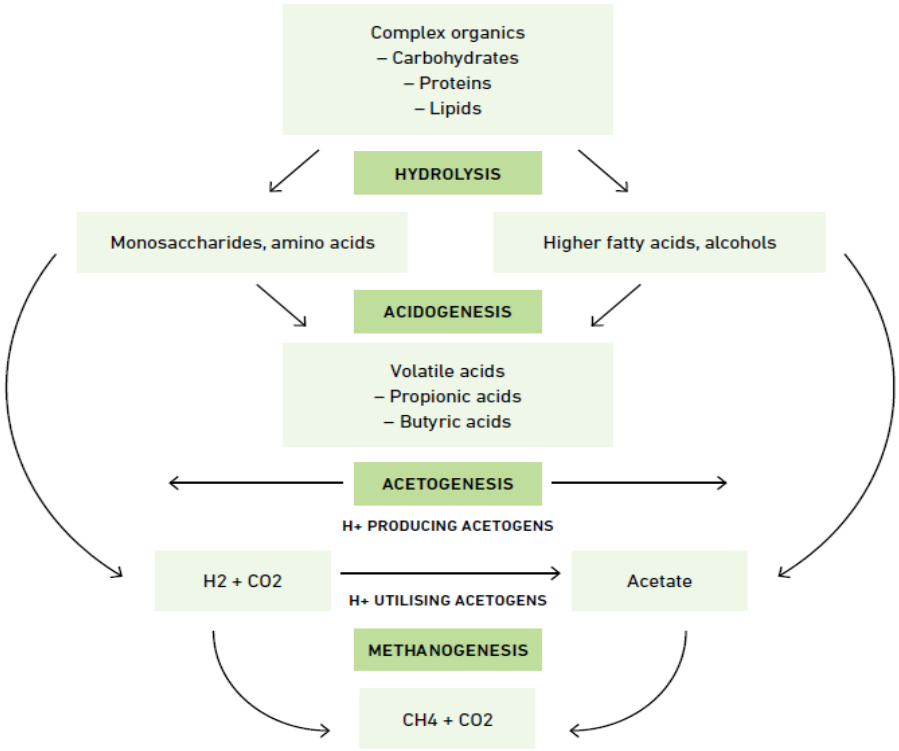


Figure 1 – Stages of anaerobic digestion (derived from Pullen et al., 2015)

The first stage in the AD process is hydrolysis, in which complex organic molecules such as proteins, fats, polysaccharides and heterogeneous organics are hydrolysed into soluble molecules including simple sugars (monosaccharides), fatty acids, amino acids and alcohols (Pullen et al., 2015; Munisamy et al., 2017). It is a rate-determining step that can limit the overall digestion rate, especially when solid waste substrates are used. In this step, microorganisms convert insoluble organic compounds in the substrate into soluble organic compounds. The optimum conditions for hydrolysis are a temperature of 30–50°C and pH of 5–7 (Azman, 2016).

The second stage is the fermentation stage, in which acidogenesis and acetogenesis occur simultaneously. Soluble organic compounds that were formed in the hydrolysis stage are degraded and converted into CO_2 and H_2 by the acidogenic bacteria. Acetic acid and hydrogen, by-products of the hydrolysis step, are digested by fermentative microorganisms, forming higher-chain organic

compounds such as volatile fatty acids (VFAs). During the acidogenesis stage, the products from the hydrolysis stage are metabolised by acidogenic bacteria to form short-chain volatile acids (e.g. butyric acid, acetic acid, propionic acid, valeric acid, hydrogen (H_2) and ammonia (NH_4). Acetic acid is the most significant organic acid used as a substrate by methane-forming microorganisms. Various studies have shown that VFA concentrations can fluctuate significantly in digesters operating at different pH.

During the acetogenesis phase, the short-chain VFAs are converted to acetic acid and additional H_2 and NH_4. During the fermentation stage, if the rate of acetic acid production is higher than the rate of its utilisation, accumulation of acetic acid and VFAs will lower the pH. This acidification can cause toxic shock to methane-forming bacteria and inhibit the AD process. The acetogenesis phase is vital because it reflects the efficiency of biogas production. Approximately 70% of AD-derived methane is formed through the reduction of CH_3COO^-T, which is the key intermediary product of the digestion process, as well as about 25% of CH_3COO^- and 11% of H_2).

The products of the fermentation stage are essential for the growth and metabolism of methanogenic bacteria in the final stage of AD (Munisamy et al., 2017). During methanogenesis in the final stage, methanogenic bacteria, characterised by hydrogen-utilising and acetoclastic methanogens, produce methane and CO_2 using hydrogen and acetic acid, respectively, through a series of reducing steps. Some of the products formed from the hydrolysis stage are also directly used by methanogens. They are anaerobes that are highly sensitive to small amounts of oxygen and are essential to the AD process because they grow slowly. in addition, methanogenic microorganisms require higher pH levels than exist in previous stages of AD. The effectiveness of these organisms is shown by the removal of organic matter in terms of chemical oxygen demand (COD) or biochemical oxygen demand (BOD) in the methanogenic stage, since prior stages merely convert organic matter from one form to another (Bajpai, 2017). The volatile solids content of the digestate can also be used to evaluate the success of the process.

Optimum performance of AD depends on pH, temperature, substrate and different groups of microorganisms that are involved in the methane production process. A delicate biological balance between acidogenesis and methanogenesis maintains the stability of the digestion process of organisms; optimal ammonia concentration can ensure sufficient buffer capacity of the methanogenic medium in AD (Rajagopal et al., 2013). Departures from optimum conditions may cause inhibition of the AD process, usually indicated by an accumulation of VFA as well as a decrease in methane production. Amino acids from VFA production, especially in protein-rich wastes, are degraded into ammonia through a deamination process. Weiland (2000) reported that VFA at more than 2000 mg/L (acetic acid) had an inhibitory effect on AD. Moreover, when organic substances that contain nitrogen are broken down, the nitrogen is converted into ammonia and then forms ammonium when ammonia is dissociated in water. The balance between ammonia, temperature and pH influences the inhibitory effect. Total ammonia nitrogen (TAN) ranging from 1500 to 7000 mg/L has been reported to be the cause of instability of the AD process (Hejnfelt and Angelidaki, 2009). Another study showed that there was an inhibition effect when ammonia-nitrogen (NH_4^+) concentration was more than 3500 mg/L

and at pH 7 (Weiland, 2000). Apart from TAN inhibiting the AD process, free ammonia nitrogen (FAN) is considered to be the main cause of inhibition of methanogenic organisms; FAN concentration is dependent on TAN, pH and temperature. Fernandes et al. (2012) reported that FAN represented less than 1% of total ammonia when anaerobic digesters were operated at pH 7 and 35°C, whereas FAN increased by 10% at pH 8 and the same temperature. FAN concentration at thermophilic (55°C) conditions was reported to be six times higher than under mesophilic conditions at the same pH (Kayhanian, 1999).

Biochemical methane potential (BMP) tests are accepted industry practice for measuring the methane potential and biodegradability of wastewater and waste biomass. Sample bottles are stored at a stable temperature of either 35°C or 55°C and mixed constantly for 30–60 days. Methane generated from AD of organic contents is measured and usually expressed relative to the mass of volatile solids or COD added. Moreover, the biodegradability of the substrate is expressed by dividing cumulative methane volume by theoretical cumulative methane volume, which is obtained by the chemical ratio of 1 g COD = 0.35 mL CH_4 at standard temperature and pressure conditions (Angelidaki and Sanders, 2004). BMP tests of different wastes lack standardisation (Elbeshbishy et al., 2012; Filer et al., 2019). The accuracy of BMP tests is affected significantly by selection of blank and control bottles, head space flushing, mixing, pH control and methane production monitoring and correction methods (Filer et al., 2019). Elbeshbishy et al. (2012) investigated the effect on BMP of two approaches: widely used blank seed assay versus pre-incubated inoculum in digestion of primary sludge and food waste at different waste-to-inoculum ratios. Labatut et al. (2011) used BMP to determine the potential and biodegradability of complex organic substrates (such as dairy manure); they found that substrates rich in lipids and easily degradable carbohydrates yielded the highest methane potential, while more recalcitrant substrates with high lignocellulosic fractions gave the lowest methane yield.

Anaerobic Digestion of Single Substrates

1.1 Materials and Methods

1.1.1 Sample Preparation and Characterisation

The first phase of this experimental program focused on biogas production from samples of waste produced during food processing or from the treatment of wastewater generated in the food industry. Eleven samples were collected and delivered to RMIT University laboratories. All substrates were stored in glass jars and refrigerated at 4°C. Table 1 describes 10 samples and their sources.

All the samples were characterised for a range of physical and chemical properties, including total solids (TS), volatile solids (VS), total nitrogen (TN), total phosphorous (TP), ammonium (NH_4), chemical oxygen demand soluble (CODs), pH, volatile acids (VAs), carbon to nitrogen (C/N) ratio and metals (K, Fe, Mg and Ca). These characteristics are summarised in Table 2.

Table 1 – Description of the food waste substrates

SUBSTRATE	ID	DESCRIPTION
Chicken Litter	CL	Litter collected from a broiler farm in the Gippsland area. Litter consists of bedding material (saw dust or pine bark) and bird droppings. After each batch of birds matures, litter is removed from sheds in high volumes.
Cow Manure	CM	Fresh cow manure scrapped from the floor of a dairy post milking at Ellinbank Research Facility in Gippsland.
Fats Oil Grease	FOG1	Collected from a food processing facility, recovered from a dissolved air flotation (DAF) unit using coagulation and flocculation processes.
Fats, Oils, Greases	FOG2	Collected from a food processing facility; a DAF unit is used to meet a trade waste agreement. An acid cracking method is utilised (hydrochloric acid).
Supermarket Waste	SMW1/ SMW2	Food waste from supermarkets is de-packaged and processed with green waste. Whilst materials can vary due to types of food waste, TS remain consistent.
Thickened Food Waste Concentrate	TC	Collected from food processing facility. This organic waste is the solid waste stream generated from dewatering using a centrifuge; a flocculant is utilised to enhance the dewatering.
Waste Activated Sludge	WAS	Solid waste stream product from industrial wastewater treatment plant. Dewatering via belt press with a flocculant.
Waste Food Oil	WFO	Collected from food processing facility. Liquid waste stream from dewatering and centrifuge methods.
Wheat Straw	WS	Wheat straw collected from the Gippsland area. Material is used for animal feed and bedding in farming practices.
Biochar	BC	Recovered from a pyrolysis process. The biochar sample was originally construction timber, chipped and pyrolysed.

Characterisation for TS, VS, TN and TP was carried out in triplicate as a minimum. The samples were centrifuged (Eppendorf 5702, Germany) at 4.4 rpm for 15 min and then filtered through a 0.45 µm filter paper (mixed cellulose esters membrane filter, Advantec, Japan), to measure the soluble constituents' CODs, soluble NH_4 and VAs. Samples were characterised in duplicate and the process was repeated if variation in measurement was greater than 10%. TS, VS, CODs and NH_4 were measured at regular intervals to monitor variation in sample characteristics during storage. Liquid substrates and substrates rich in oil, fat and grease were homogenised (warmed to 25°C, then mixed using a magnetic mixer for 30 seconds) before use in characterisation. The inoculum used in the experimental determination of biogas production was collected from a mesophilic anaerobic digester (37°C) at the Yarra Valley Waste-to-Energy facility that processes commercial food wastes. The inoculum was stored in polypropylene plastic containers at 35°C for several days to stabilise it (i.e. degrade residual organics).

1.1.2 Analytical Methods

Total solids and VS were measured according to the Standard Methods 2540B and 2540E, respectively. The CODs, NH_4 and VAs were determined using HACH methods 8000, 10031 and 8196, respectively. pH was measured using a calibrated pH meter (ThermoOrion, Model 550A). The C/N ratio was determined using a LECO (TruMac) Analyser.

Table 2 – Substrate characteristics

Sample	*TS*	*VS*	*TP*	*TN*	*NH_4*	*CODs*	*pH*	*VA*	*C/N*
	%	%	mg/L	mg/L	mg/L	mg/L	-	mg/L	-
CL	73.4	63.4	3691.5	7058	1680	55,400	-	443.5	25.2
CM	10.5	8.3	768.5	1251	-	88,500	-	564.5	20.3
FOG1	10.9	10.1	37.4	3793	59	5,400	5.7	112.0	7.7
FOG2	5.6	5.1	498.0	3053	9	600	-	235.5	8.7
SMW1	60.4	59.0	-	845	21	357,900	5.3	9,212.5	180.2
SMW2	81.1	75.6	-	725	-	-	-	516.5	-
TC	29.1	27.7	95.8	851	25.25	191,400	-	14,207.5	30.3
WAS	12.7	7.2	-	2214	265	3500	6.9	3325	4.8
*WFO**	97.4*	97.4	1050.8	365	77	213,900	-	618.5	-
WS	90.1	85.3	-	-	-	-	-	-	173.5
BC	36.1	31.7	249.3	230	-	-	-	543	50.7
Inoculum	3.74	3.0			1092				13.2

* This sample was oily; hence the TS standard methods could not be applied. After being kept in the oven at 105°C for more than 6 hrs, the sample was 97.4% of original weight.

1.1.3 Experimental Method: BMP for Single-Substrates

Substrate potential for biogas production was determined using BMP tests. The substrates and inoculum were mixed at a ratio of 1:2 gVS:gVS and loaded into 500 mL bottles (referred to in this report as anaerobic digestion reactors). For each substrate, the BMP test was carried out at TS concentrations of 2% and 4%; and each test was run in duplicate. (The organic waste samples received had varying TS of 3.7–81.1%, therefore they were diluted using deionised water to achieve TS of 2% and 4% inside the BMP reactors.) For each TS concentration, two control bottles that contained the same VS mass were used in the reactors, were operated at the same conditions. The biogas produced from the control was subtracted from the biogas produced from reactors that received substrates, i.e. the biogas reported is the net production.

To ensure anaerobic conditions during the test, the reactors were flushed with nitrogen for 1 minute and then suba-seals were used to seal the reactors. The reactors were kept in a shaking incubator under mesophilic conditions (37°C) at 100 rpm and monitored for biogas and methane production. The BMP test was stopped when biogas production stabilised (i.e. a plateau in cumulative biogas production was observed). Biogas production was measured using a water displacement unit and biogas composition was determined using gas chromatography. At the conclusion of the BMP test, the key performance parameters – NH_4, pH, TS, VA and VS – of the digestate were measured.

Results and Discussion

Biogas production for all substrates was determined according to the BMP test. The potential for biogas production for all the food wastes (referred to in this report as substrates) was determined at TS concentrations of 2% and 4%, the range at which wet AD is typically operated. The cumulative biogas production curves for all food waste samples tested are shown in Figures 2–12. The contents of all AD reactors, the digestate, were characterised at the end of the BMP test. These characteristics are summarised in Table 3.

The cumulative biogas production for the substrates CL, CM, WS and BC (Figures 2, 3, 11 and 12) showed a similar biogas production trend. Slightly higher biogas production was obtained at 4% TS during the first 18 days, after which the AD reactors with 2% TS produced biogas at a higher rate. The CL and CM substrates had lower biogas production rates than WS, indicating that they have lower degradability (e.g. for CL and CM at 4% TS, 67.5 and 88.6 mL biogas were produced, respectively, from day 13 to 21, compared to 108.7 mL for WS). The cumulative biogas yields for CM at 2% and 4% TS were approximately 400 and 500 m^3 biogas/ton VS, respectively. The biomethane yield for both 2% and 4% TS were 329 and 259 m^3 CH_4/ton VS, respectively. Labatut et al. (2011) discussed individual BMP assays on dairy manure from six farms and reported that the average and range of specific methane yield were 243 mL/CH_4 and 127–329 mL/CH_4 VS added, respectively. The range of methane yield reported by El-Mashad and Zhang (2010) was 241 mL/CH_4 VS added. The methane yield for CM reported in this study is well within these ranges.

As discussed by Azman (2016), the hydrolysis rate of CL and CM is limited by their rich protein content. The concentrations of NH_4 in the AD reactors of 4% TS for CL, CM and BC were 1636, 1362 and 1513 mg/L, respectively, which are at the boundaries of reported NH_4 inhibition range of 1500–2000 mg/L. Inhibition for the AD reactor of 4% TS for CM, resulting in lower cumulative biogas production, was observed. This was due to amino acids from VFA production, which are further degraded into ammonia by the deamination process. VA (measured as acetic acid) in the AD reactor with 4% TS for CM was almost three times higher than in the AD reactor with 2% TS.

Biogas production from FOG1, FOG2 and TC (Figures 4, 5 and 8) showed similar production rate and trend for the AD reactors with 2% and 4% TS. These three substrates showed low production rate during the first 12–18 days, after which the reactors with 2% TS had a higher production rate; in contrast, gas production in the reactors at 4% TS decreased after 18 days, resulting in a yield 56–80% lower than at 2% TS. The lower gas production at 4% TS was most likely due to the accumulation of NH_4: 2143.6, 2081.5 and 1504.1 mg/L NH_4 were measured for FOG1, FOG2 and TC, respectively, at 4% TS, compared to 542.1, 1148.3 and 920.2 mg/L NH_4 at 2% TS. FOG1 and FOG2 showed a similar trend with CM with respect to VA accumulation: VA in reactors for FOG1 and FOG2 with 4% TS were almost three times and 11 times more than in the reactors with 2% TS. This suggests that reactors with 4% TS were inhibited because FOG samples are high in lipids. During mono-digestion, long-chain fatty acids form in agglomerated particles and are known to be inhibitory at low concentrations (Zhang et al. 2013).

The substrates SMW1 and SMW2 (Figures 6 and 7) showed similar biogas production for 2% and 4% TS%. Both substrates showed slow biogas production during the first 10 days, but the reactors recovered and increased production for the remainder of the BMP test.

Figure 10 shows that for the WFO, there was a lag phase in biogas production during the first 3 days, indicating the constituents of the WFO were slowly degradable organics and inhibition was most likely due to the accumulation of VAs. Both reactors at 2% and 4% TS continued to show low gas production for 20 days, after which the reactors that had WFO at 2% TS began to recover, though the VAs at the end of the BMP test were still high at 2285 and 6738 mg/L for the reactors with 2% and 4% TS, respectively. Inhibition of biogas production due to accumulation of VAs is the main challenge for AD reactors processing substrates rich in fat and oil, as has been widely recognised by AD operators and many researchers.

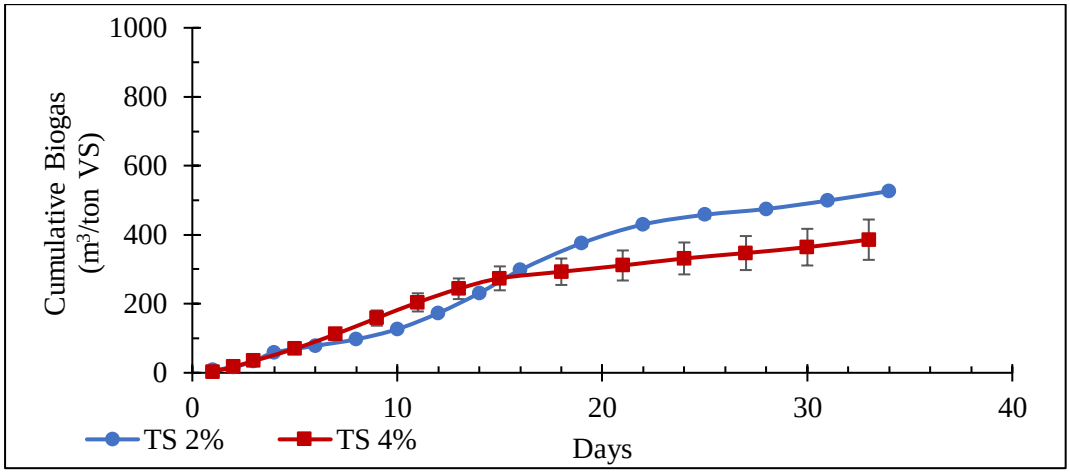


Figure 2 – Cumulative biogas production for chicken litter (CL)

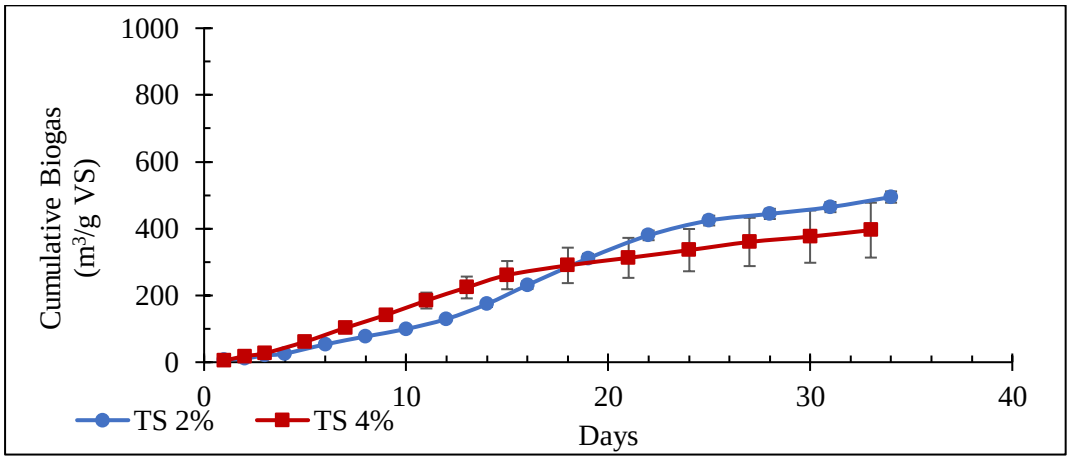


Figure 3 – Cumulative biogas production for cow manure (CM)

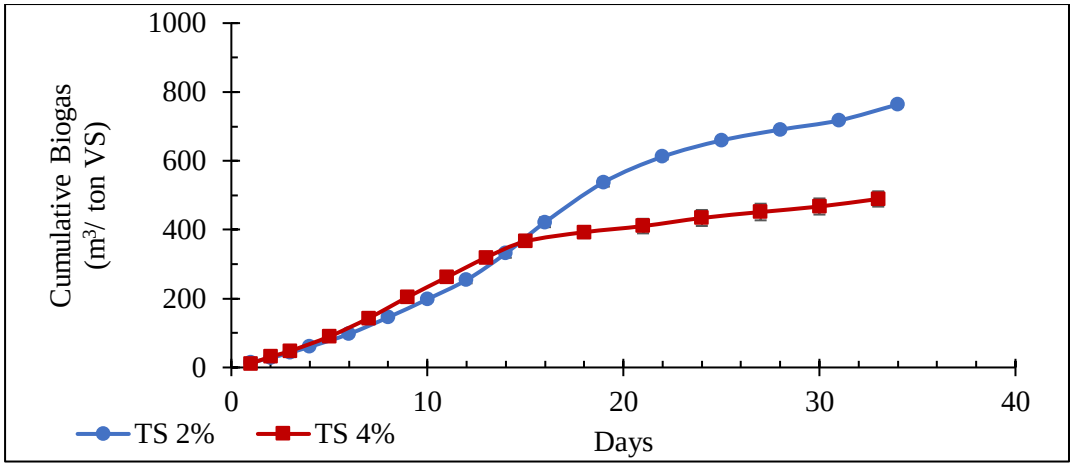


Figure 4 – Cumulative biogas production for fats, oils, greases (FOG), DAF with coagulant

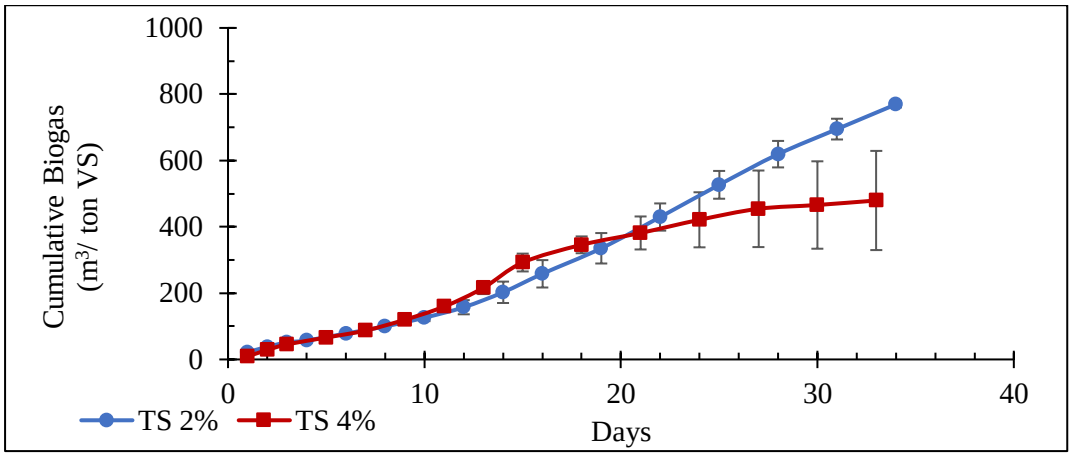


Figure 5 – Cumulative biogas production for fats oils and greases (FOG2), acidic DAF process

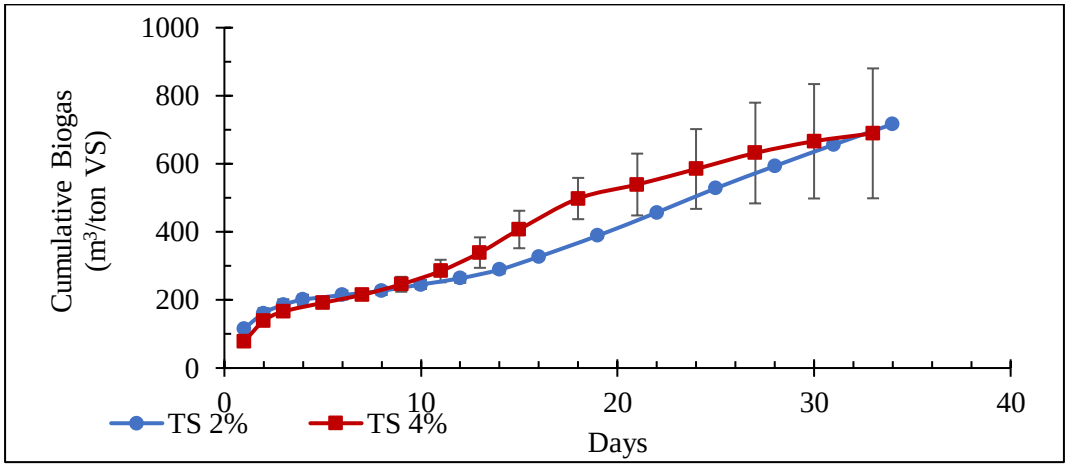


Figure 6 – Cumulative biogas production for supermarket waste sample 1 (SMW1)

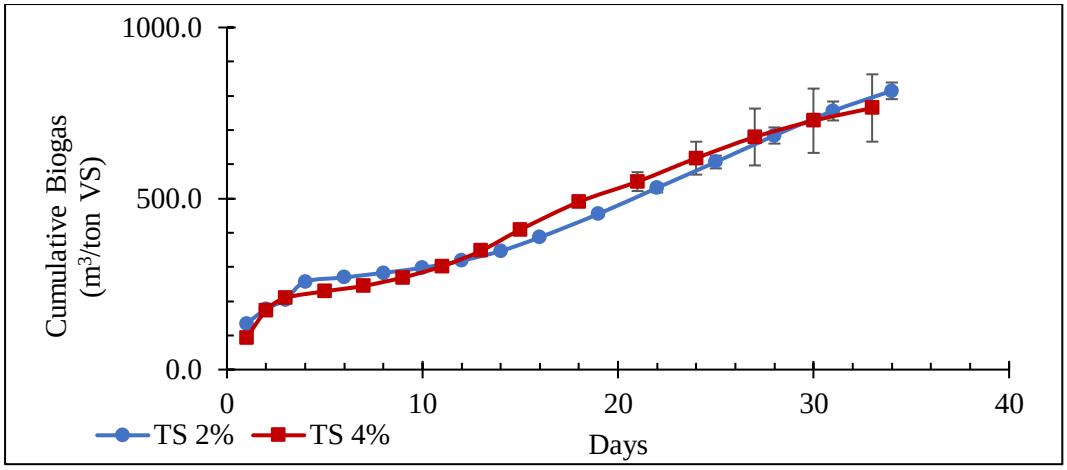


Figure 7 – Cumulative biogas production for super market waste sample 2 (SMW2)

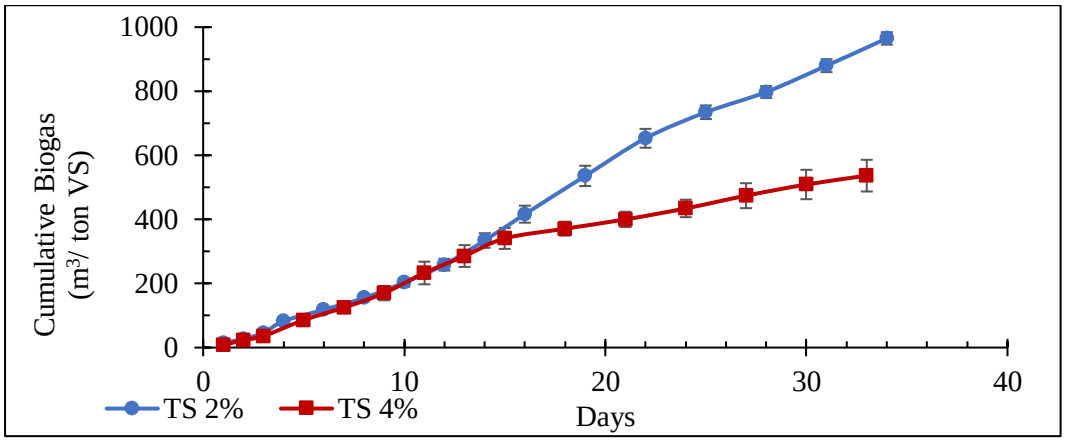


Figure 8 – Cumulative biogas production for thickened food waste concentrate (TC)

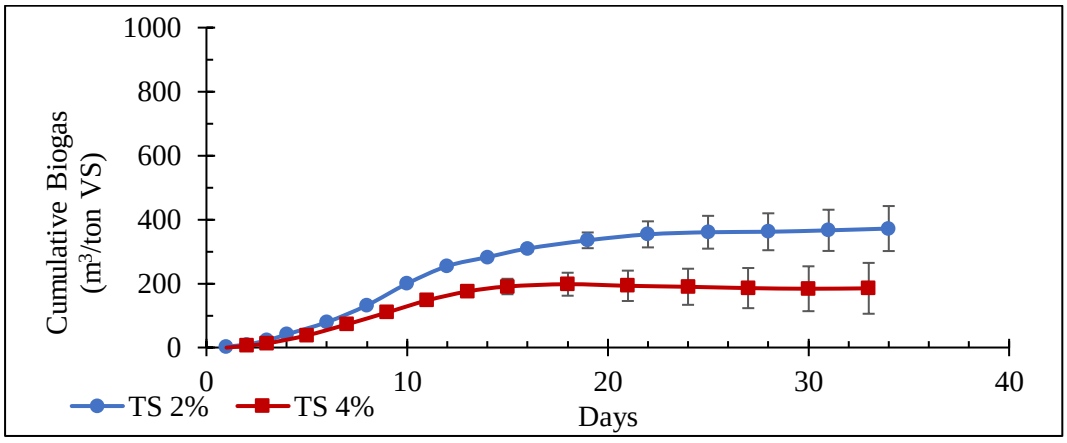


Figure 9 – Cumulative biogas production for waste activated sludge (WAS)

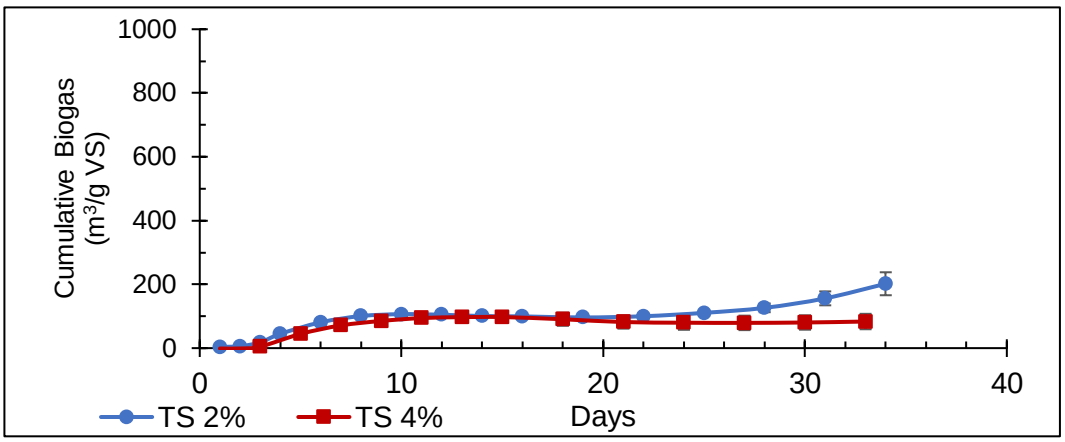


Figure 10 – Cumulative biogas production for waste food oil (WFO)

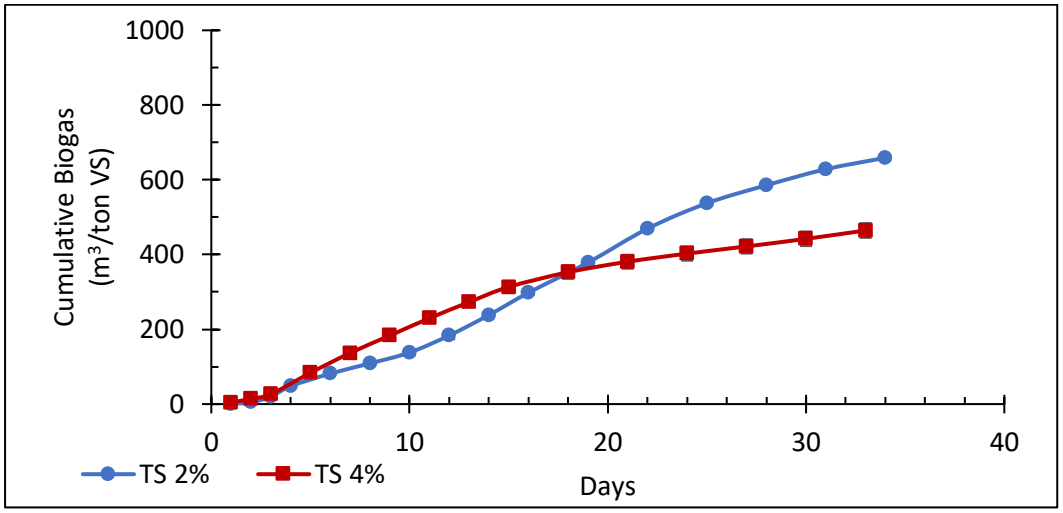


Figure 11 – Cumulative biogas production for wheat straw (WS)

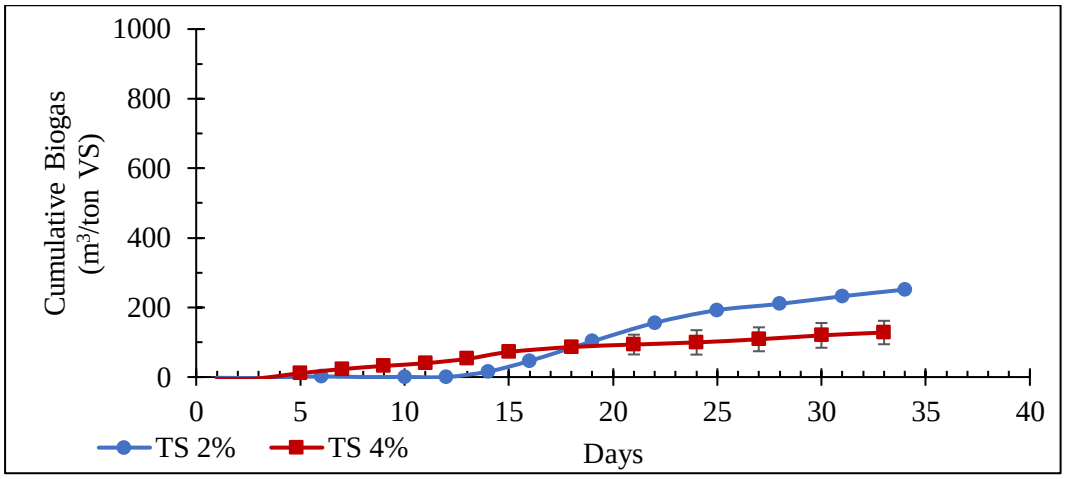


Figure 12 – Cumulative biogas production for biochar (BC)

Table 3 – Reactor performance parameters at end of the mono-digestion BMP tests

	TS	*TS Removal*	*VS Removal*	*NH_4*	*VA*	*pH*
UNIT	%	%	%	mg/L	mg/L	-
CL	2	47%	51%	640.2	799.5	7.46
	4	75%	81%	1635.8	644.5	7.48
CM	2	28%	29%	897.4	447.5	7.39
	4	58%	62%	1362.5	1259.5	7.54
FOG1	2	63%	68%	542.1	217.5	7.59
	4	77%	82%	2143.6	629.0	7.71
FOG2	2	77%	85%	1148.3	71.0	7.32
	4	77%	83%	2081.5	789.5	7.85
SMW1	2	71%	77%	790.9	42.0	7.28
	4	73%	79%	1360.6	920.0	7.54
SMW2	2	73%	79%	390.2	175.0	7.32
	4	69%	73%	1236.3	831.00	7.56
TC	2	40%	44%	920.2	101.0	7.44
	4	62%	66%	1504.1	801.5	7.54
WAS	2	23%	29%	1653.7	635.5	7.61
	4	65%	66%	2053.3	1135.5	7.76
WS	2	43%	46%	802.8	419.5	7.37
	4	64%	69%	1660.0	869.5	7.49
WFO	2	32%	33%	926.1	2284.5	7.00
	4	63%	67%	1829.9	6737.5	6.83
BC	2	67%	71%	808.7	467.0	7.51
	4	78%	83%	1513.3	733.5	7.43

Ammonium ions or ammonia were produced from proteins and amino acids during AD. The presence of high ammonia concentrations is known to inhibit AD (Lehtomaki et al., 2007; Nie et al., 2015; Zahan et al., 2018) and is toxic to methanogenic bacteria, thus inhibits methanogenesis and reduces biogas production or, in extreme cases, stops production entirely (Zahan et al., 2018). TAN ranging from 1500 to 7000 mg/L has been reported to be the cause of the instability of the AD process (Hejnfelt and Angelidaki 2009). Apart from TAN inhibiting the AD process, FAN is considered to be the main cause of inhibition of methanogenic organisms, where FAN concentration is dependent on TAN, pH and temperature. In the 2% TS AD reactors, the final TAN concentration ranged from 390.2 mg/L (SMW2) to 1653.7 mg/L (WAS). Therefore, it is likely that inhibition due to TAN did not occur in the 2% TS AD reactors, because concentrations were in general below the inhibition range of 1,500–2,000 mg/L (Zahan et al., 2016). For the AD reactors at 4% TS content, TAN concentrations increased to between 1236.3 mg/L (SMW2) and 2143.6 mg/L (FOG). As the TAN concentration increased, in particular above 1513.3 mg/L (e.g TAN concentration for BC at 4%), inhibition occurred and the production of biogas decreased.

The results derived from WS, despite its high C/N ratio TAN concentration, are attributed to the structure of the substrate. Plant-based material such as WS are lignocellulosic, and in particular the lignin content can prevent penetration by microbes, which limits hydrolysis (Tian et al., 2018). The limitation of hydrolysis reduces biogas yield. The degradation of lignin is slow, and often incomplete; thus, pre-treatment or co-digestion is usually applied to optimise the AD of mono-substrates.
Zhu (2007) reported that AD of CM can be carried out efficiently when the C/N ratio is 15. Kumar et al. (2010) found that a C/N ratio of 13.9–19.6 is acceptable for digestion. In this study, the C/N ratio for CM was 20. Optimisation of the C/N ratio of substrates is a common strategy for optimising the AD process and reducing ammonia toxicity (Wang et al., 2012; Hassan et al., 2016; Zahan et al., 2018). Research has shown that as the C/N ratio of a substrate or multiple substrates increases above 20, the production of biogas increases and improves process stability (Rahman et al., 2017; Zahan et al., 2018). Hence, co-digestion of animal manure with high carbon content improves the C/N ratio, which then increases biogas production. In this study, the substrates with the highest C/N ratio, SMW1/2 (180.2) and WS (173.5), showed high biogas production, but TC had the highest yield of 965.0 m3/tonVS although it had a much lower C/N of 30.3. The substrates FOG1 and FOG2 produced high biogas yield though they had a low C/N ratio. The findings with respect to co-digestion are discussed in the next section.

1.2 Summary of the mono-digestion BMP results

- The TC at 2 %TS had the highest yield of 965 m^3/tonVS.
- SMW1, SMW2, FOG1 and FOG2 all produced biogas yield within the range of 763.8–814.8 m^3/ ton VS, at 2% TS.
- The WFO and BC substrates showed the lowest biogas production, producing 201.0 and 251.3 m^3/tonVS, respectively, at 2% TS.
- Biogas production from all substrates at 4% TS showed the same trend observed at 2% TS.

1.3 Biogas Yield and Bioenergy Production from the Food Wastes

The biogas yields, i.e. the maximum biogas production, for all substrates at 2% and 4% TS are summarised in Tables 4 and 5.

Table 4 – Biogas, biomethane and bioenergy equivalent for all substrates at 2% and 4% TS

	TS 2%			TS 4%		
	*Biogas Yield	Bio-methane Yield	Bio-energy Equivalent	*Biogas Yield	Bio-methane Yield	Bio-energy Equivalent
Sample	m^3/ton	m^3/ton VS	MJ/ton VS	m^3/ton	m^3/ton VS	MJ/ton VS
CL	526.7±5.1	351	13,280	385.8±58.5	257	9,709
CM	494.5± 16.9	329	12,432	395.5±82.2	259	9,774
FOG1	763.8±6.2	538	20,318	489.3±22.2	351	13,277
FOG2	769.5±9.1	546	20,629	479.5±149.6	323	12,203
SMW1	716.8±4.5	462	17,449	689.6±190.9	445	16,824
SMW2	814.8±24.3	525	19,861	764.6±98.4	498	18,808
TC	965.0±19.5	652	24,638	536.6±49.5	346	13,097
WAS	371.9±70.4	251	9,500	185.0±79.5	130	4,919
WFO	201.0 ±36.0	126	4,758	83.4±24.2	53	2,013
WS	659.1±7.1	436	16,473	464.5±19.7	299	11,284
BC	251.3±3.2	177	6,704	127.9±33.7	257	9,709

CH_4 energy content of 37.8 MJ/m^3 was used *indicative only

Table 5 – Physical, biochemical characteristics and methane yield of mono-digestion substrates (by others)

Samples	TS (g/kg)	VS (g/kg)	VS/TS	C/N ratio	Biogas yield (mL/gVS)	Methane yield (mL/gVS)	TAN avg/ final (mg/L)	TAN final (mg/L)	Free NH_3 avg (mg/L)	Free NH_3 final (mg/L)	References
Chicken manure	26.8%	62.3%	ND	8.84	311.4	126.9	1783	2568	51.2	177.5	Wang et al. 2012
Poultry manure	40.0%	75% DM	-	-	130–270 Nm^3/t	70–140 Nm^3/t	-	-	-	-	Biogas fundamentals
Raw dairy manure	124	102.1	0.82	ND	-	242.7	-	-	-	-	Labatut et al., 2011
Manure separated liquid	57.5	40.5	0.71	ND	-	261.3	-	-	-	-	Labatut et al., 2011
Dairy manure	14.4%	76.6%	ND	22.1	437	177.4	572	837	5.3	11.9	Wang et al. 2012
Cattle manure	ND	4 g VS/L	ND	5.2	19.0	5.0	-	-	-	-	Zhang et al. 2013
Cattle manure	ND	2.7 g VS/L	ND	5.2	28.0	6.0	-	-	-	-	Zhang et al. 2013
Cattle manure	ND	2 g VS/L	ND	5.2	38.0	9.0	-	-	-	-	Zhang et al. 2013
Dairy waste	0.1–7%		ND	11.4–13.6	-	100–850	-	-	-	-	Xu et al. 2018
Slaughterhouse waste	2–28.3%		82.7–93.6%	3–6	-	200–500	-	-	-	-	Xu et al. 2018

Cattle slurry	6–11%	75–82% DM		-	20–30 Nm^3/t	11–19 Nm^3/t	-	-	-	-	Biogas fundamentals
Cattle manure	20–25%	68–76% DM		-	60–120 Nm^3/t	33–36 Nm^3/t	-	-	-	-	Biogas fundamentals
Fruit & vegetable waste	7.4–17.9%		83.4–95.3%	15.2–18.9	-	160–350	-	-	-	-	Xu et al. 2018
Used vegetable oil	991	988.8	1	ND	-	648.5	-	-	-	-	Labatut et al., 2011
Cabbage, raw	78.6	72	0.92	ND	-	256.5	-	-	-	-	Labatut et al., 2011
Potato, raw	177.4	163.5	0.92	ND	-	334.5	-	-	-	-	Labatut et al., 2011
Food waste	ND	8 g VS/L	ND	21.1	621.0	410.0	-	-	-	-	Zhang et al. 2013
Household & restaurant food waste	4–41.5%		88.7–95.1%	11.4–36.4	-	460–530	-	-	-	-	Xu et al. 2018
Waste pet food	86–93%		74.6–94.5%	10–25	-	150–500	-	-	-	-	Xu et al. 2018
Suspended fat, oil & grease (FOG)	267.2	229.7	0.86	ND	-	402.3	-	-	-	-	Labatut et al., 2011
Settled FOG	128.4	112.6	0.88	ND	-	413.4	-	-	-	-	Labatut et al., 2011

FOG	1.3–3.2%		86–93.9%	22.1	-	400–1100	-	-	-	-	Xu et al. 2018
Wheat straw	86.1%	90.6%	ND	81.1	317.5	121.2	37.8	53.3	0.2	0.2	Wang et al. 2012
Switchgrass	930.1	904.9	0.97	ND	-	122.2	-	-	-	-	Labatut et al., 2011
Grass silage	25–50%	70–95% DM	-	-	170–200 Nm^3/t	93–109 Nm^3/t	-	-	-	-	Biogas fundamentals
Prunings & clippings	12%	87% DM	-	-	175 Nm^3/t	105 Nm^3/t	-	-	-	-	Biogas fundamentals

Anaerobic Co-digestion

To determine the potential for enhancing biogas yield of the available substrates, AcoD batch BMP tests were performed. Taking into consideration the spatial distribution of available substrates (Appendix A) and key operating parameters such as TS and the C/N ratio, five mixtures of substrates were investigated for their potential as feedstock.

1.4 Materials and Methods

The food wastes (substrates) that showed high biogas yield through the mono-substrate BMP tests were investigated further, with the aim of enhancing their biogas production potential through co-digestion with other substrates. The spatial distributions of these wastes, as well as their C/N contents (i.e. their C/N ratio), were selected as key selection criteria for co-digestion. Based on these criteria, six feedstocks (i.e. mixtures of substrates) were formed. Seasonal variations in the quantity and availability of the selected food wastes were not considered, because these were not in the scope of the experimental program. The six feedstocks and their composition are listed in Table 6.

Table 6 – Anaerobic co-digestion feedstock composition and characteristics

Feedstock Label	*Feedstock Components*	*Substrate %*	*Substrate %*	*Substrate %*	*C/N*	*TS (%)*	*VS (%)*
A	TC-WFO-SMW1	TC 16	WFO 76	SMW 8	33.30	4.0	3.4
B	CL-WS-FOG	CL 94	WS 5	FOG 1	27.80	4.0	3.3
C	CL-CM	CL 98	CM 2	-	24.83	4.0	3.3
D	WS-FOG	WS 74	FOG 26	-	26.13	4.0	3.4
E	CL-WS-CM	CL 96	WS 3	CM 1	27.53	4.0	3.3
F	TC-WFO-SMW2	TC 16	WFO 73	SMW2 11	33.30	4.0	3.4

1.5 Analytical Methods

All samples – the substrates that were assessed for biogas potential using mono-digestion batch BMP tests, as well as the new substrates – were reanalysed to determine changes to their characteristics (i.e. quality parameters). Fresh inoculum was collected and characterised for TS and VS, measured according to the Standard Methods 2540B and 2540E, respectively. Samples were characterised in duplicate and for some samples, characterisation was repeated twice or three times until a satisfactory standard deviation was achieved. CODs, ammonia and VAs were determined using HACH methods 8000, 10031 and 8196. Liquid substrates were homogenised for 30 seconds prior to use in characterisations or being added to the experimental design.

1.6 Experimental Method: Anaerobic Co-Digestion BMP Tests

The substrates were added in the BMP reactors, as outlined in Table 5. The anaerobic co-feedstock compositions, the TS and VS concentrations inside the reactors and the C/N of the combined substrates are shown in Table 5. The BMP test was performed with 14 batch anaerobic laboratory reactors, two for each feedstock and two blanks (received only inoculum). The reactors, 1L total volume, were kept in an orbital shaker at 100 rpm and a temperature of 37°C for 35 days. At the end of the ACoD, BMP test, the digestates in all reactors were characterised in terms of COD, NH_4, pH, TS, VAs and VS and selected metals Ca, Fe, K and Mg.

1.7 Results and Discussion

To optimise ACoD of a substrate, selected substrates of different C/N ratios can be incorporated to form a feedstock with a balanced C/N ratio. The aim of ACoD is to minimise the risk of inhibition due to ammonia and VA accumulation. ACoD also enriches the anaerobic bacterial diversity in anaerobic reactors and has been reported to improve methane production by up to 85% compared to mon-digestion of substrates (Hassan et al., 2016; Zahan et al., 2018).

The cumulative biogas yield for the AcoD of the different substrates, feedstocks A to F, are shown in Figures 13–18. The biogas and biomethane yield for the six feedstocks are summarised in Table 7. The ACoD experiment using the available substrates showed that the optimal combination of substrates was WS and FOG (feedstock D) with a C/N ratio of 26, resulting in a biogas yield of 820.0 m^3/ton VS (methane of 531.2 m^3/ton VS). FOG is a popular organic substrate for AD due to its high methane potential. In co-digestion, addition of WS to FOG may have diluted the lipids found in FOG, enabling more lipids to be digested and resulting in higher biogas production. On the other hand, the reactor with Feedstock B (CL-WS-FOG) had a biogas yield of 606 m^3/ ton VS, which showed that addition of WS did not increase biogas production even though C/N was slightly higher at 28. Feedstock A (TC, WFO, SMW1) and feedstock F (TC, WFO, SMW2) had biomethane yields of 395.8 and 243.7 m^3/ ton VS, respectively. Feedstocks A and F were similar – the only difference was the type of supermarket waste used (i.e. SMW1 and SMW2). Even with a C/N ratio of 33 for both feedstocks A and F, the results showed the effect of the variability in the composition and characteristics of supermarket wastes, emphasising the need for assessment of the quality and quantities of feedstocks over multiple seasons and the impact of these variations on biogas and biomethane yield.

Dilution of lipid-rich wastes with other co-substrates has been reported previously (Hatamoto et al. 2007). Angelidaki and Ahring (1997) also recommended dilution of oil-type wastes before they are added to anaerobic digesters because of the rapid decrease in pH during the hydrolysis stage. Reactors with feedstock C (CL-CM) and E (CL-WS-CM) had biogas yields of 452 and 422 m^3/ ton VS, respectively. Feedstock E (with added WS) and feedstock C (CL-CM) had similar cumulative biogas production; the lower biogas yield for the C2 reactor was assumed to be due to some protein matter from the CM that was biodegrading slowly. However, it was observed that at day nine, the biogas yield of feedstock E was 50% greater than that of feedstock C. This suggests that the biodegradability

of CL-CM improved when WS (a substrate with higher C/N ratio) was added as a co-digestion substrate.

Overall, the co-digestion C/N ratios used in this study ranged between 25 and 33. This range is higher than that reported in Zhang et al. (2013), where the co-digestion of food waste and CM, with a C/N ratio of 16–18, yielded biogas production of 537 m^3/ton VS.

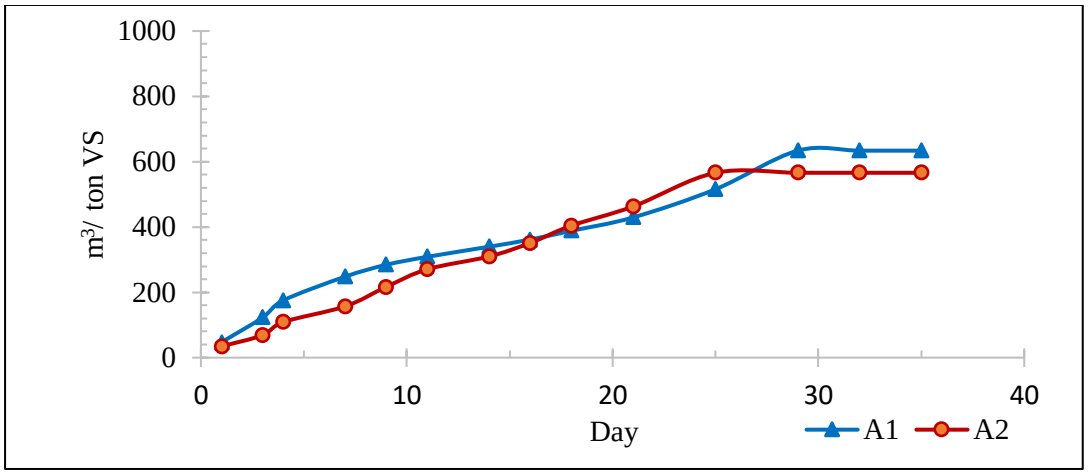


Figure 13 – Cumulative biogas production from AcoD feedstock A (TC, WFO, SMW1)

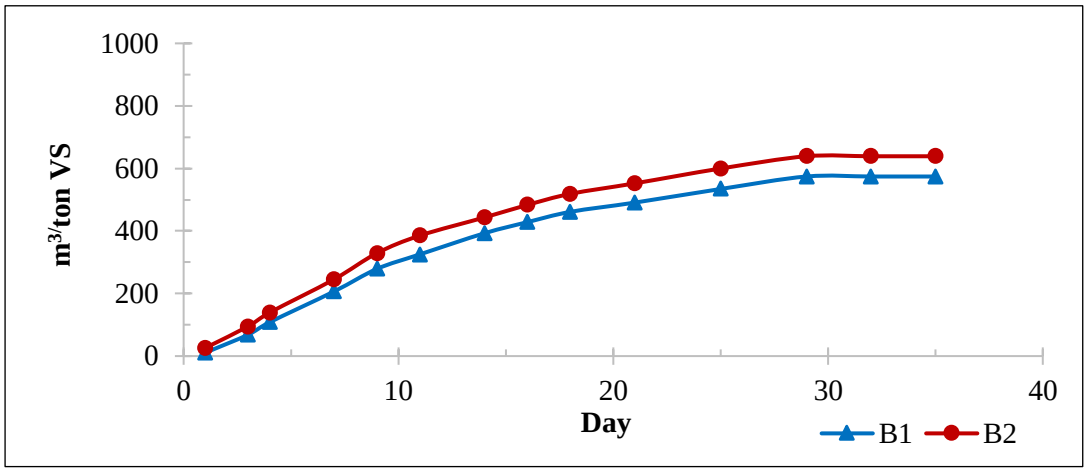


Figure 14 – Cumulative biogas production from AcoD feedstock B (CL-WS-FOG)

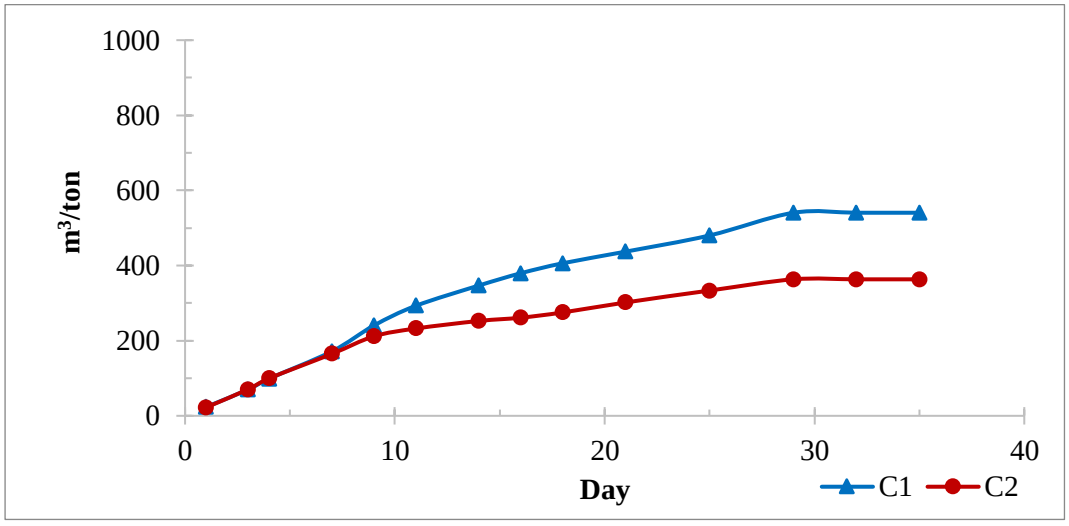


Figure 15 – Cumulative biogas production from AcoD feedstock C (CL-CM)

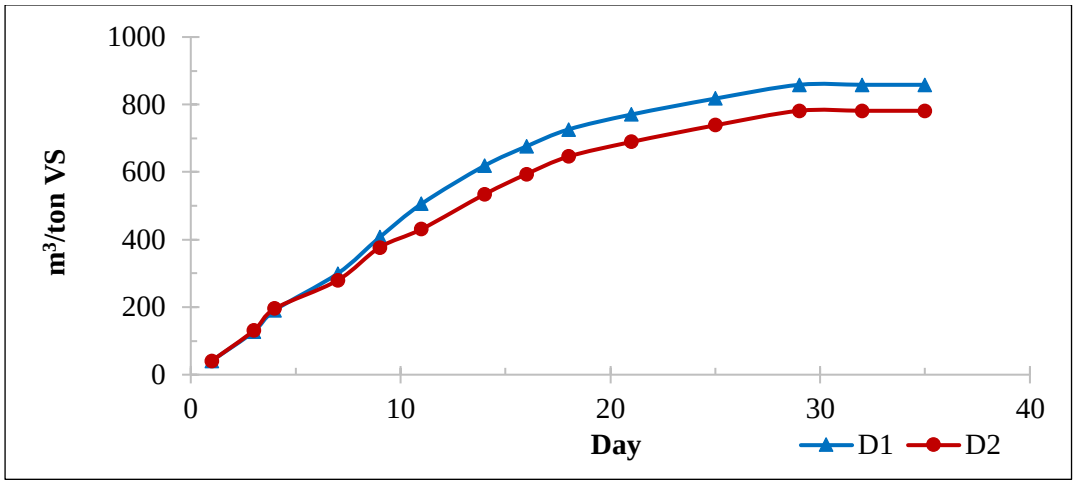


Figure 16 – Cumulative biogas production from AcoD feedstock D (WS-FOG)

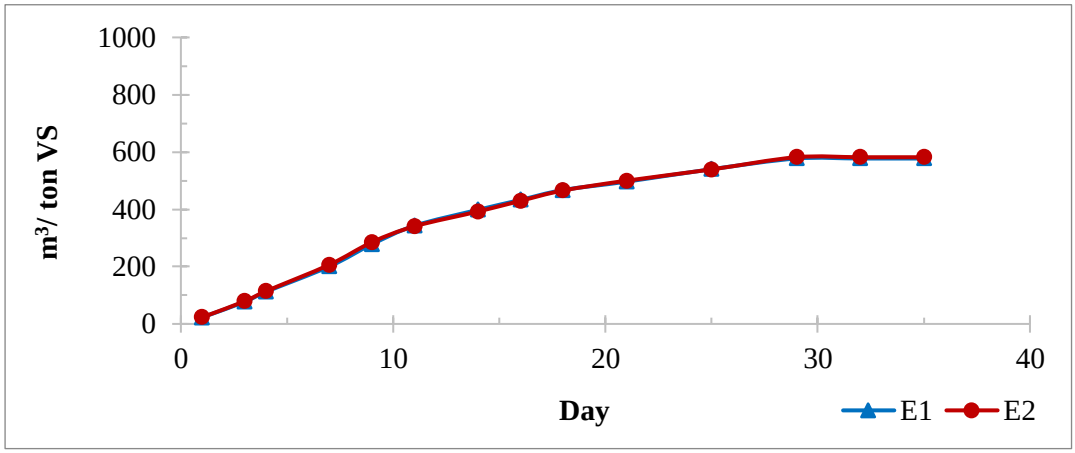


Figure 17 – Cumulative biogas production from AcoD feedstock E (CL-WS-CM)

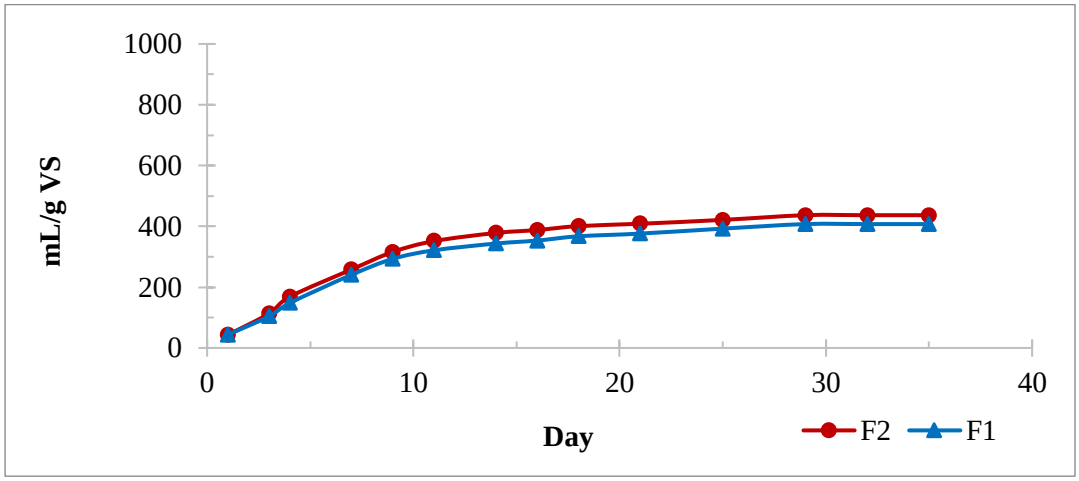


Figure 18 – Cumulative biogas production from AcoD feedstock F (TC, WFO, SMW2)

Table 7 – Biogas yields for the co-digested substrates

Feedstock Label	Substrates (sub) Sub1: Sub2: Sub3	Substrates rations %	Biogas m^3/ton VS Actual	Biogas m^3/ton VS Calculated	Enhanced Biogas Yield	Methane m^3/ton VS
A	TC: WFO:	16: 76: 8	599.9±47.9	367.5	63%	395.8
B	CL: WS: FOG	94: 5: 1	606.6±45.8	535.8	13%	396.0
C	CL: CM	98: 2	452.0±75.5	526.3	-14%	294.1
D	WS: FOG	74: 26	820.0±54.4	686.3	19%	531.2
E	CL: WS: CM	96: 3: 1	579.6±3.1	529.9	9%	375.0
F	TC: WFO: SMW2	16: 73: 11	422.0±20.7	388.6	9%	243.7

Gas chromatography was utilised to determine the composition of the biogas. At the conclusion of week 1, methane percentage ranged from 52.7% to 66.3%. As the experiment continued, methane composition increased to 59.8–68.6%.

1.8 Anaerobic Co-digestion Reactor Performance

At the conclusion of the ACoD BMP tests, the digestates in the BMP reactors were analysed to determine their key characteristics. The characteristics of digestate in the reactors that received feedstocks A–F are outlined in Table 8.

Final TAN concentrations from AcoD batch experiments ranged from 2005.7 mg/L to 2315.7 mg/L. Compared with mono-digestion, the TAN concentration in co-digestion effluent was obviously higher; concentrations in all systems with multiple substrates were above 2000 mg/L. This agrees with Hartmann et al.'s (2003) finding that co-digestion alleviates the inhibitory effect of high ammonia and sulphide concentrations. Even though they exceeded the inhibition range, the results presented in this report indicate that, in most cases, minimum ammonia inhibition occurred in co-digestion. System C, comprising CM and CL, experienced visible anaerobic inhibition with low daily biogas production, though it did not have the highest TAN concentration. System A demonstrated potential inhibition from day 7 to 15 but was able to acclimatise to ammonia concentrations and recovered from inhibition.

The TAN and VA concentrations in the reactor with feedstock D that exhibited the highest methane yield were 2230 and 2350 mg/L, respectively. Moreover, it was observed that VA concentration for one sample of feedstock A was very high at 7366 mg/L, as well as for both duplicates for feedstock F at 8899 and 9247 mg/L, respectively. This was due to the addition of WFO and TC as co-substrates. Apart from that, feedstock A and feedstock F shared the highest C/N ratio of 33, whereas the other reactors had C/N ratios of 25–28. There was VA accumulation, showing that the AcoD process was inhibited; this was confirmed by the lowest methane yield of 244 m^3/ton VS for feedstock F. On the other hand, feedstock A had a higher methane yield of 396 m^3/ton VS. This again emphasises the importance of the effect of variability in the composition and characteristics of supermarket wastes. Also, this suggests that the TS content of feedstock with WFO and TC should be less than 4% to minimise the inhibition effect on co-digestion.

Final pH ranged from 6.8 for feedstock F to 7.7 for feedstock A. The optimal range for ACoD pH is 6.5–7.5. The results did not demonstrate inhibition due to low pH or the generation of sour digestion, with most systems falling within the optimal range. Similarly, pH did not affect the final net biogas production; system A, with the highest pH, produced the second-highest yield.

The concentrations of calcium, iron, potassium and magnesium were measured in the digestate. McCarty and McKinney (1961) reported that the inhibition concentration of potassium was 10 g/L. Based on the data in Table 9, potassium concentration was below the inhibition limit. Trace elements such as Mg and Ca have been reported to play an important role in enhancing methanogen activity in AD (Zhang et al., 2013).

Table 8 – Characterisation of digestate for feedstocks A to F

	COD(s) (mg/L)	*NH_4 (mg/L)*	*TN (mg/L)*	*TP (mg/L)*	*VA (mg/L)*	*Ca*	*Fe*	*K*	*Mg*
A	13,659	2005.7	2,861	322.4	2410	509.7	16.5	578.3	22.5
	20,802	2265.5	3,139	547.5	7366	488.2	16.0	588.9	15.5
B	13,536	2006.0	2,666	326.0	2122	522.6	16.4	708.0	27.3
	11,778	2121.0	2,680	259.8	1882	718.4	15.8	662.8	23.0
C	12,509	2123.2	2,850	311.5	1958	593.7	16.2	683.2	30.8
	14,009	2190.4	3,106	377.2	2250	521.7	16.4	689.3	25.1
D	14,150	2222.4	2,926	327.3	2209	758.4	15.5	587.1	28.7
	15,918	2235.5	3,134	486.2	2324	699.9	17.8	620.6	44.4
E	11,692	2041.7	2,848	333.7	1780	738.2	18.8	711.6	32.2
	12,277	2133.4	3,204	296.6	1946	828.1	17.5	715.1	41.8
F	24,177	2221.1	3,563	668.6	8899	886.5	18.4	558.5	36.6
	24,632	2315.7	3,140	640.8	9247	592.9	24.2	562.3	28.0

Table 9 – Physical, biochemical characteristics and methane yield of co-digestion experiments (by others)

Samples	Experimental design	C/N ratio	Biogas yield (mL/ gVS)	Methane yield (mL/ gVS)	TAN avg (mg/L)	TAN final (mg/L)	Free NH_3 avg (mg/L)	Free NH_3 final (mg/L)	References
Dairy manure: cattle manure: wheat straw	DM/CM = 100:0 + WS	C/N 25:1	458.6	211	412	635	7	11.6	Wang et al. 2012
Dairy manure: cattle manure: wheat straw	DM/CM = 0:100 + WS	C/N 25:1	389.7	156.2	932	1453	22.4	41.7	Wang et al. 2012
Dairy manure: cattle manure: wheat straw	DM/CM = 50:50 + WS	C/N 25:1	581.8	234.7	713	1025	8.5	23.5	Wang et al. 2012
Dairy manure: cattle manure: wheat straw	DM:CM:WS = 48.7 : 48.7 : 2.6	C/N 15:1	2100 mL	11–34%	2614	-	223	-	Wang et al. 2012
Dairy manure: cattle manure: wheat straw	DM:CM:WS = 45.5 : 45.5 : 9.0	C/N 20:1	2600 mL	16–40%	1800	-	70	-	Wang et al. 2012
Dairy manure: cattle manure: wheat straw	DM:CM:WS = 42.3 : 42.4 : 15.4	C/N 25:1	5200 mL	37–51%	712	-	9.1	-	Wang et al. 2012
Dairy manure: cattle manure: wheat straw	DM:CM:WS = 39 : 39 : 22	C/N 30:1	5800 mL	30–52%	604	-	7.5	-	Wang et al. 2012
Dairy manure: cattle manure: wheat straw	DM:CM:WS = 35.6 : 35.6 : 28.8	C/N 35:1	4200 mL	21–42%	444	-	2.2	-	Wang et al. 2012
Dairy manure : food waste	33% DM, 67% FW	-	-	390	-	-	-	-	Zhang et al. 2013
Dairy manure : switchgrass	75% manure, 25% switchgrass	-	-	207.8	-	-	-	-	Labatut et al., 2011
Dairy manure : Used oil	75% manure, 25% used oil	-	-	360.6	-	-	-	-	Labatut et al., 2011

Food waste: cattle manure	FW : CM = 2 (gVS/L)	15.8	570	388	-	-	-	-	Zhang et al. 2013
Food waste: cattle manure	FW : CM = 3 (gVS/L)	17.1	526	352	-	-	-	-	Zhang et al. 2013
Food waste: cattle manure	FW : CM = 4 (gVS/L)	17.9	536	343	-	-	-	-	Zhang et al. 2013
Straw : food waste	17% COD straw, 83% COD FW	-	-	390	-	-	-	-	Kim et al. 2003
Sewage sludge : food waste	20% VS sewage sludge, 80% VS FW	-	-	260	-	-	-	-	Sosnowski et al. 2008
Sewage sludge : food waste	75% vol sewage sludge, 25% vol FW	-	-	440	-	-	-	-	Yong et al. 2015

Summary

The BMP tests for the mono-digestion of a range of food wastes showed that the solid wastes collected from DAF units at food waste processing plants (e.g. TC, FOG1, FOG2, SMW1 and SMW2) had biogas yields of 965.0, 769.5 and 814.8 m^3/tonVS, which corresponded to a methane yield of 652.0, 546.0 and 525.0 m^3/tonVS. The results of mono-digestion BMP tests demonstrated that food wastes have high potential as a feedstock for bioenergy production using AD technology. In addition, the BMP tests showed that AD at 2% TS produced higher biogas and methane yield than AD at 4% TS. In the meantime, mono-digestion of the food wastes assessed in this study indicated that there is high potential for accumulation of TAN and/or VAs, which correlates with the substrates' compositions.

The food wastes assessed had C/N ratios ranging from 4.78 to 180.2. ACoD of a mixture of two and three food wastes, selected mainly on the basis of their C/N ratio and location, showed potential to enhance biogas yield from these food waste samples compared to their yield under mono-digestion conditions. The outcomes from this study show that there is great potential for AD for bioenergy production from food wastes in Victoria, which will have the additional benefit of diverting these resources from landfill. The publication of this study should encourage bioenergy project developers to undertake their own substrate analyses to build their business case for Anaerobic Digestion projects.

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Appendix A

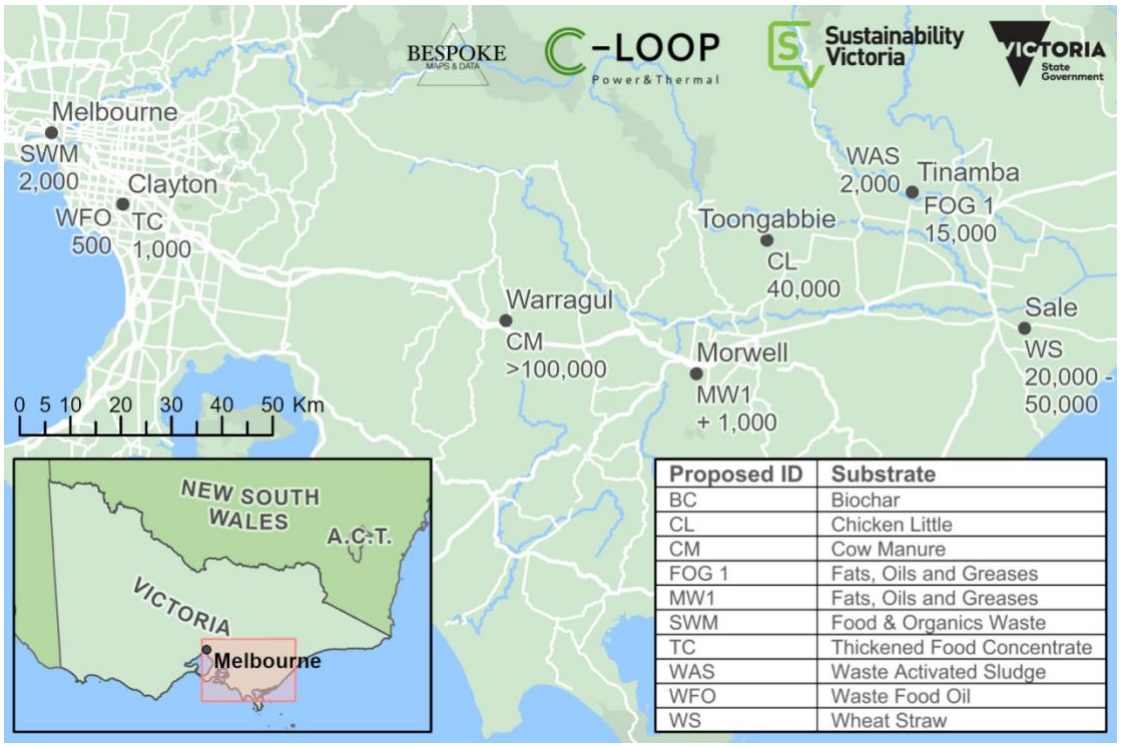

Figure A.1: Spatial Distribution of Organic Waste Substrates including defined tonnage within, Victoria, Investigated for their Potential for biogas Production