March 2026

FINAL REPORT

Waste-to-Energy: Fueling Sustainable Wastewater Treatment with Food Waste

END FOOD WASTE COOPERATIVE RESEARCH CENTRE
Australian Government Department of Industry, Science and Resources
Cooperative Research Centres Program

Author(s):

Paul D Jensen

End Food Waste Cooperative Research Centre, Australian Centre for Water and Biotechnology at The University of Queensland

Lisa Bai

End Food Waste Cooperative Research Centre, Australian Centre for Water and Biotechnology at The University of Queensland

Estabraq Al-gertan

End Food Waste Cooperative Research Centre, Australian Centre for Water and Biotechnology at The University of Queensland

EFW CRC Publication 2026/019"

Level 1, Wine Innovation Central Building, Cnr Hartley Grove and Paratoo Road, URRBRAE SA 5064
enquiries@endfoodwaste.com.au +61 8 8313 3564

Final Report Version 2 – 19/09/2024

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Panel Review Statement

End Food Waste CRC recognises the value of knowledge exchange and the importance of objective peer review. It is committed to encouraging and supporting its research teams in this regard. The author(s) confirm(s) that this document has been reviewed and approved by the Project Leader and Industry Partner.

This project has also been evaluated by the End Food Waste CRC publication review panel. These reviewers evaluated its:

- Methodology articulated clearly
- Positioning of findings within the current literature
- Acknowledged compliance with food safety standards
- Conclusions against results
- Relevant human and/or animal ethic approvals obtained

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Table of Contents

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

List of Figures

List of Tables

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Industry Partner Foreword

This research has been an important step in improving our understanding of anaerobic digestion and co-digestion. Its purpose was to define the limits for accepting co-substrates under current operating conditions, and it has successfully achieved this. The findings will help us maximize the benefits of co-digestion while reducing operational risks, supporting the safe and efficient operation of our facilities.

The outcomes have clear value for the business. The research provides greater clarity regarding co-digestion loading capacity, allowing the organization to plan future organic waste processing with confidence. It also supports our sustainability goals by making better use of spare digester capacity, helping to divert organic waste from landfill. In addition, it improves our understanding of opportunities for renewable energy generation, potential energy cost savings, and revenue forecasting. Together, these benefits help offset operational costs and contribute to keeping sewage treatment services affordable for the local community.

Collaborating on this project has highlighted the value of strong partnerships between industry and research in addressing complex challenges. Testing and validating processes in a real-world demonstration facility has been critical in building confidence and reducing uncertainty. These outcomes will inform future decision-making and investment strategies, positioning the organisation to respond proactively to future co-digestion opportunities.

____

Huijuan Li

Senior Process Engineer

21/01/2026

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Executive Summary

Australia generates around 7.6 million tons of food waste per year and if poorly managed the decomposition of food waste results in health risks, unpleasant odours and significant environmental pollution. This food waste typically contains a large fraction of organic material (that can be used to generate renewable energy) along with valuable nutrients including nitrogen, phosphorus and potassium (that can be used to generate renewable fertilizers). Anaerobic Digestion (AD) is a core platform technology able to convert food waste into energy and fertilizers and is already widely applied at municipal waste treatment facilities, many of these existing facilities have spare treatment capacity intended to support long term population growth. The import of Solid Food Waste (SFW) and other Food Industry Wastes (FIWs) into existing waste treatment infrastructure for co-treatment in AD presents a promising strategy to valorise food waste and boost renewable energy production. This strategy utilises spare treatment capacity and maximises the value obtained from Australia's existing infrastructure investments. If executed successfully, co-treatment of food waste has the potential to transform sewage treatment plants from larger consumers of electricity into net energy exporters while providing established pathways and markers for the recycling of nutrient content of food waste as part of an organic fertilizer product called biosolids. Co-substrates are available from a broad range of industries that generate organic wastes including many sources of food waste and food industry waste. The physical, chemical and biological properties of these different waste streams can be very different, impacting the compatibility of these waste streams with existing AD plants, the economics of treatment and risk challenges for sewage treatment plants. Poor selection of co-treatment wastes and poor management of import operations has the potential to upset the sewage treatment plant operations resulting in high cost, unstable operations and in extreme cases, environmental damage.

This project conducted extensive laboratory testing on the composition and energy potential of selected commercial food industry wastes and developed a flagship co-digestion test facility to examine co-treatment strategies at scale, under real world conditions. The core goals of this work were to guide ongoing full-scale anaerobic co-digestion at the host site to provide tangible economic and environmental benefits, with outcomes being transferable from the host site to broader industry.

Target Food Industry Wastes in this project included Macerated Solid Food Waste (SFW), Grease Trap Waste (GTW), Beverage Processing Waste (BEV) and waste from Dairy and Milk Processing (DMP). All wastes tested in this project were highly concentrated in comparison to sewage therefore, all potential co-substrates will have stronger impact on biogas potential relative to import volumes. The methane potential of GTW was highest at 72 m^3/wet ton (~2.45 GJ/ton heat energy) followed by SFW at 64 m^3/wet ton (~2.2 GJ/ton heat energy), by comparison the methane potential of sewage sludge is 10 m^3/wet ton (as added to the current AD process). The concentrations of the waste streams were found to be highly variable which requires the digester loading strategy to be managed to maintain safe and stable process operation.

The pilot-scale test facility was operated for over 400 days and examined co-substrate loadings from 10% of organic load up to 50% of organic load. The test facility was assessed against performance models developed from laboratory testing. The test facility was impacted by several external disruptions, however during periods of stable operation, comparisons of the pilot plant performance and batch tests show that over 88% of the degradable material was converted to methane in the pilot plant. The biogas composition was typically 60-63% CH_4 and 37-40% CO_2. In general, the methane production from the test facility was similar to the performance model predictions, while the solids destruction performance exceeded the lab-based performance models.

Biogas production in the test facility was highly dynamic and was impacted by both the co-substrate loading strategy and the digester mixing strategy. Depending on co-substrate loading strategy, dynamic biogas production rates varied from approximately 50 to over 250 L/m^3/hr over a typical 24-hour cycle. From these results, monitoring changes in average daily biogas production are not sufficient to understand the impacts to co-substrate dosing and biogas dynamics must be considered to ensure gas handling limits are not exceeded. Further work is required to assess the relationship between co-substrate dosage and the peak intensity of the biogas response.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

The digestate product was collected from the pilot test facility at multiple time points and assessed for reuse potential against the current End of Waste codes in Queensland. The Food Industry Wastes examined in this project contained significantly lower heavy metal concentrations when compared to mixed sewage sludge, which had a dilution effect and resulted in lower contaminant levels in the resulting digestate. At the FIW addition rates, the contaminant dilution effect may be enough to shift the Class of biosolid from Contaminant Grade C to Contaminant Grade B, opening up additional reuse options (subject to an appropriate pathogen reduction step). However, while co-treatment of food waste reduced the contaminant levels of the biosolid, there was a negative impact on the product quality and there is a significant risk that the dewatered sludge will not meet stability requirements for land application, however these results were preliminary and additional data is needed to complete assess the risk.

Overall, the pilot test facility was largely successful in validating the laboratory results as a predictor of steady state behaviour at larger scale, however this work also demonstrates an acclimation period between process changes. While the process adapted to disruptions or shifts in operating conditions, there are periods during the acclimation period where the process is not stable and the product may not meet regulatory requirements. Further work is required to better understand these transition periods and develop operational strategies to minimise risk during these periods.

Renewable energy produced from full-scale co-treatment during the project offset an estimated 2300 t/y of Scope 2 greenhouse gas emissions and importing these waste streams may have avoided an additional 5,000 t/y of landfill emissions. Impacts from this project will continue beyond the project life due to new and existing commercial arrangements. Waste import levels are expected to expand, in part due to knowledge gained in the project, which will further increase the GHG impacts resulting from import activities. The project demonstrates that future GHG avoidance of 15,000 t CO_2-e per year could be achieved at a single large WWTP in the future, without compromising existing plant operations. This impact could be expanded to multiple WWTP of similar size, already existing in large population centres throughout Australia. Broad uptake of project outcomes and co-digestion strategies throughout Australia could result in annual GHG reductions of over 200,000 tonnes per year.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

1. Introduction

1.1 Project Background

Australia generates over 14 million tons of organic waste per year with approximately 50% of this waste currently disposed to landfill. Of this organic waste, approximately 7.6 million tons is food waste. Food waste typically contains a large fraction of organic material along with valuable nutrients including nitrogen, phosphorus and potassium. If poorly managed the decomposition of food waste results in health risks, unpleasant odours and significant environmental pollution (Muratçobanoğlu et al., 2020, Wang et al., 2018). For example, methane generated from decomposition of food waste is a greenhouse gas that contributes to about 3% of Australia's total greenhouse gas emissions (FIAL, 2021). However if recovered or recycled, food waste could represent a significant resource stream. For these reasons, management of food waste and food industry waste (FIW) has emerged as a significant environmental and economic issue.

Around the globe, various methods have been implemented to manage the growing volume of organic waste generated from human activities and recover energy or nutrient resources. Gasification and incineration are examples of waste-to-energy technologies more commonly used outside Australia. However, these technologies are rarely economic at scales relevant to Australia and can have significant secondary environmental impacts. For example, the combustion reactions that occur during incineration generate toxic compounds in a flue gas product, which, if not treated, cause air pollution and bring about environmental and health risks (Paranjpe et al., 2023). Combustion technologies may allow for recovery of some nutrients, such as phosphorus, but will also volatilize nitrogen into harmful flue gas components. Biological technologies, such as anaerobic digestion (AD), are alternative methods for recycling food waste while also addressing the growing global energy demand (Khalil et al., 2019, Oladejo et al., 2020).

AD represents a sustainable method for recycling food waste by converting organic material into useful by-products. The core product of AD is biogas. The specific composition of biogas varies based on the composition of the digested organic material however the major components are typically methane (CH_4) and carbon dioxide (CO_2) with trace amounts of siloxanes, hydrogen sulfide (H_2S) (Wickham et al., 2016), oxygen (O_2), nitrogen (N_2), and carbon monoxide (CO). Biogas can be upgraded to close to 100% methane and fed into the natural gas grid or can be burned on site using co-generation systems to efficiently generate renewable heat and power (Wickham et al., 2016). AD also preserves nutrients from the wastes in a digestate product, which may enable recycling as an organic fertilizer. The rich biodegradable organic matter (carbohydrates, fats, and proteins) in FIW makes it highly suitable for AD as a practical treatment pathway to mitigate both the volume and environmental impact of waste (Iacovidou et al., 2012).

Currently, AD is widely used at municipal wastewater treatment plants (WWTP), where the by-products of wastewater treatment are recycled to produce energy (from biogas) and an organic fertilizer (called biosolids). In this context, WWTPs are an existing commercial pathway contributing towards a circular economy. WWTPs are often designed and constructed with the capacity to support growing populations and the corresponding increase in wastewater flows. Consequently, many facilities have available capacity in the digesters to accommodate additional waste streams (Koch et al., 2015). Co-treatment of FIW at existing WWTPs offers a substantial opportunity for the water industry to boost its renewable energy production, thereby mitigating its environmental impact. This integrated approach supports a circular economy by converting waste into valuable resources while optimizing existing infrastructure, ultimately contributing to more resilient and sustainable urban waste management systems. However, FIW is inherently variable, with its composition in terms of carbohydrates, lipids, and proteins differing significantly based on its specific constituents. Additionally, the composition of these constituents can vary extensively depending on their cultivar and geographical origin (Iacovidou et al., 2012). The variable nature of FIW impacts the amount of co-substrate that can be handled without causing process instability, making it challenging to accurately predict the amount that can be safely added to a WWTP and making full-scale implementation of anaerobic digestion for FIW challenging.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

1.2 Key Literature

1.2.1 Anaerobic Digestion and Co-digestion

Anaerobic digestion (AD) is an established technology utilizing naturally occurring microorganisms to produce methane-rich biogas from organic wastes. Anaerobic co-digestion (AcoD) involves the simultaneous AD of two or more substrates, with the objective of processing available wastes in a more environmentally sustainable manner, maximizing biogas yields and improving stability of the AD process. Co-digestion is a significant opportunity to promote linkages and cooperation between industries, in dealing with wastes from one industry in a more environmentally sustainable manner by becoming the co-feedstock for co-digestion in another industry. Such linkages broaden the potential applications for AD by exporting wastes from smaller facilities where standalone AD is not cost-feasible, to another larger industry where it would be feasible. This contributes to broader and more sustainable waste management practices, including sustainable management of waste nutrients, such as nitrogen and phosphorus. For these reasons, the quality of residue remaining after co-digestion (termed digestate or biosolid depending on the application) is also important (Mata-Alvarez et al., 2014). Ideally biosolid or digestate is beneficially reused as a nutrient fertilizer. However, this practice is closely regulated through EoW codes and if digestate quality is compromised, then it may instead need to be disposed of at additional cost. For example, when sewage sludge is co-digested with manure, it improves biogas yield and process stability (Al Seadi et al., 2013), but strict requirements can limit the application of digestate as a fertilizer, because of heavy metals, persistent organic pollutants and pathogens (Al Seadi et al., 2013). The cost feasibility of co-digestion is determined in part by the costs of transporting wastes to the host site and in part by the cost of managing digestate residues (Mata-Alvarez et al., 2014).

Anaerobic digestion (AD) and Co-digestion have been commercially implemented for processing various organic wastes, including municipal solid waste, food waste, industrial by-products, sewage sludge, animal manure, and agricultural residues (Jensen et al., 2022). In recent years, anaerobic digestion technology has attracted research interest due to its ability to produce clean energy (Abdeshahian et al., 2016, Zhao et al., 2024).

AD is a biological process that converts organic materials into methane-rich biogas, which can be collected and used as a source for renewable energy. Figure 1 is a schematic representation of the metabolic processed involved in AD, typically represented using four key biological steps:

- Hydrolysis: During hydrolysis, carbohydrates, proteins, and lipids are broken down into their monomers (i.e. sugars, amino acids, and long chain fatty acids (LCFA)) via extracellular enzymes (Sanders et al., 2000).
- Acidogenesis/Fermentation: During acidogenesis, the soluble products from hydrolysis are converted into intermediate compounds such as volatile fatty acids (VFA), alcohols or ketones. For sugars and amino acids the conversion is achieved by fermentative bacteria (FB) and occurs via fermentation, while for LCFA the process requires anaerobically oxidation (mainly b-oxidation) in a syntrophic relationship with hydrogen consuming microorganisms. Hydrogen is a by-product of fermentation that is produced to balance wasted electrons (Zhou et al., 2018, McInerney et al., 2008).
- Acetogenesis/Secondary Fermentation: In acetogenesis, LCFA and intermediate compounds, other than acetate, are converted to acetate and hydrogen by acetogenic bacteria (AB). Acetogenesis is carried out through b-oxidation, where hydrogen (or formate) is both a reaction product and reaction inhibitor; consequently, hydrogen concentration must be limited to low levels for thermodynamic reaction feasibility. Therefore, this step is only possible through a syntropy with H_2-consuming processes (i.e. hydrogenotrophic methanogenesis, sulphate reduction etc.) (McInerney et al., 2008, Li et al., 2012).

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

- Methanogenesis: Methanogenesis is the final metabolic step in the anaerobic digestion process in which the remaining intermediate products (acetate, formate, hydrogen, carbon dioxide) are converted to methane and carbon dioxide by methanogenic archaea. There are two major pathways: acetolactic methanogenesis (AM) where acetate is cleaved to form methane and carbon dioxide; and hydrogenotrophic methanogenesis (HM) where carbon dioxide is reduced using hydrogen as an electron donor (Conrad, 2005, Qu et al., 2009).

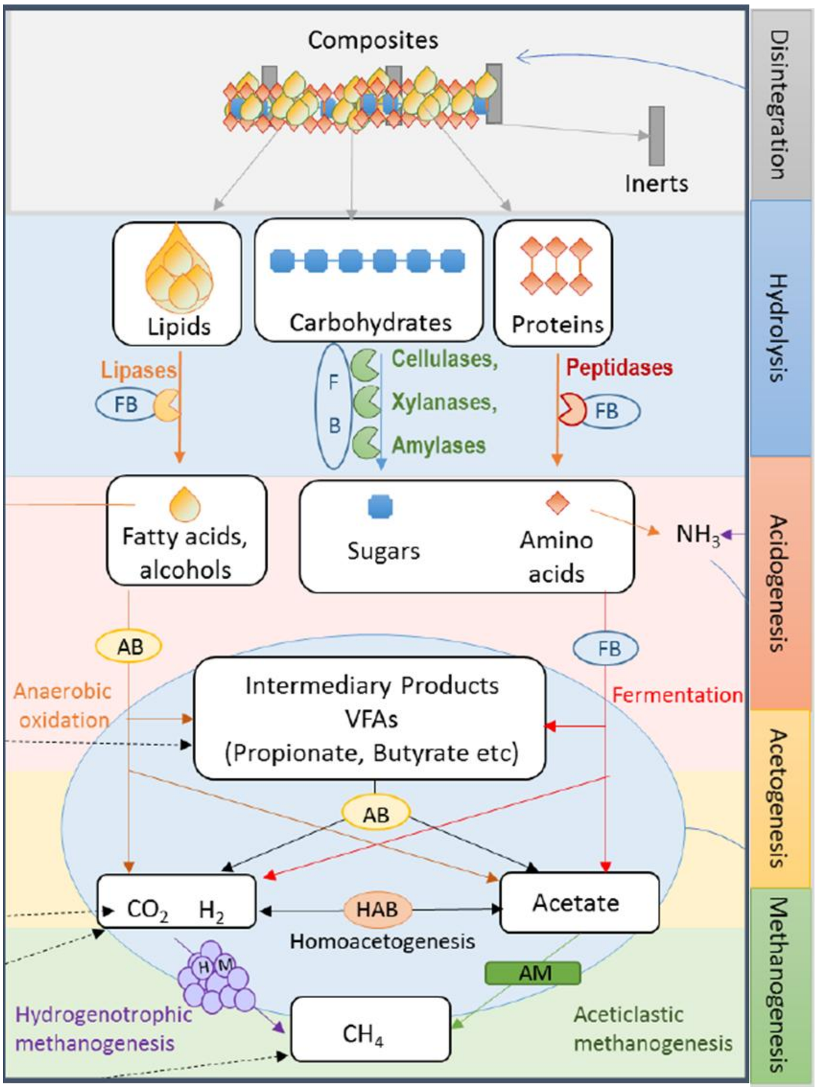


Figure 1: A schematic of key anaerobic digestion reactions, progressively breaking down composite particulate wastes into soluble intermediate products and ultimately into methane. Adapted from (Batstone et al., 2002, Macintosh, 2020).

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Successful AD requires balance between the metabolic processes shown in Figure 1 (Chen et al., 2008). Failure of the AD process is commonly caused by an imbalance between process:

a) Upstream acid-forming fermentation reactions carried out by bacteria that are responsible for the upstream reactions of hydrolysis, acidogenesis and acetogenesis; and
b) Downstream acid consuming reactions carried out by methanogenic archaea.

Imbalance in upstream and downstream microbial reactions typically leads to an accumulation of volatile organic acids (Ahring et al., 1995), which can depress pH and cause chemical inhibition, ultimately resulting in AcoD failure (Chen et al., 2008, Demirel and Scherer, 2008, Sträuber et al., 2012). It can be difficult or costly to recover from such failures, because it may require alkali dosing to increase pH of the liquid content in the failed CAP or digester (Tait et al., 2009). This imbalance and system failure can result from poor selection of AD or co-digestion mixtures or by increasing the organic loading rate of the digester beyond safe limits. Therefore, it is important to understand the impact of substrate mixtures on AD and co-digestion and to understand safe organic loading capacities.

Additional risks of Co-digestion include substrate mixtures being incompatible, again leading to overload, instability or potentially process failure. For example, it is important that wastes selected for Co-digestion decompose at a faster rate than the base substrate for which the digestion system was designed. Otherwise, the retention time and treatment capacity may need to be increased to accommodate the slower degrading waste (Al Seadi et al., 2013). Some wastes rich in Fat, oil and grease are excellent methane boosters because of high methane potential, but require very long treatment times to convert into methane (Al Seadi et al., 2013). The selection of co-digestion mixtures is very important to ensure that the digestion remains stable and reasonable.

1.2.2 Application of Anaerobic Co-digestion within Municipal Wastewater Treatment Plants

Figure 2 shows a conventional wastewater treatment process that utilises AD within the solids management train. In this process there is a primary sedimentation tank that captures suspended solids and organic matter from the raw wastewater, the resulting primary sludge can be directed to the anaerobic digester. The composition and concentration of primary sludge (PS) is highly dependent on the catchment and impacts the performance of the AD (Tchobanoglous et al., 2014). After the primary settlers, the wastewater is sent to the bioreactors where biological nutrient removal (BNR) processes are used to remove nitrogen and phosphorus from the wastewater. The BNR processes generate a biological sludge by-product called waste activated sludge (WAS), which is also fed to the digester. The volumes and characteristics of WAS are highly dependent on the operation of the bioreactors and the nitrogen removal requirements of the plant. As nitrogen discharge licenses tighten, this has the effect of increasing the energy cost of secondary treatment and produces a lower volume of WAS, but the WAS is also more difficult to digest and produces less methane. After AD the digestate is sent to the dewatering units to separate the treated biosolids from the centrate, the centrate is then sent to head of the plant where it is recycled through the bioreactors for nitrogen and phosphorus removal. In a convention WWTP the nitrogen recycled within the centrate can account for around 30% of the nutrient load entering the bioreactors. Integrating AD into a wastewater treatment plant (WWTP) offers multiple benefits, including energy recovery, sludge volume reduction, and improved biosolid quality. Co-digestion has the potential to significantly increase biogas production at a WWTP, however there may be secondary impacts, including an increase in the mass of solids captured through dewatering and increase in the mass of nitrogen recycled to the BNR process. Co-substrates with a very high degradable fraction and inherently low nitrogen and phosphorus contents would be preferred.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

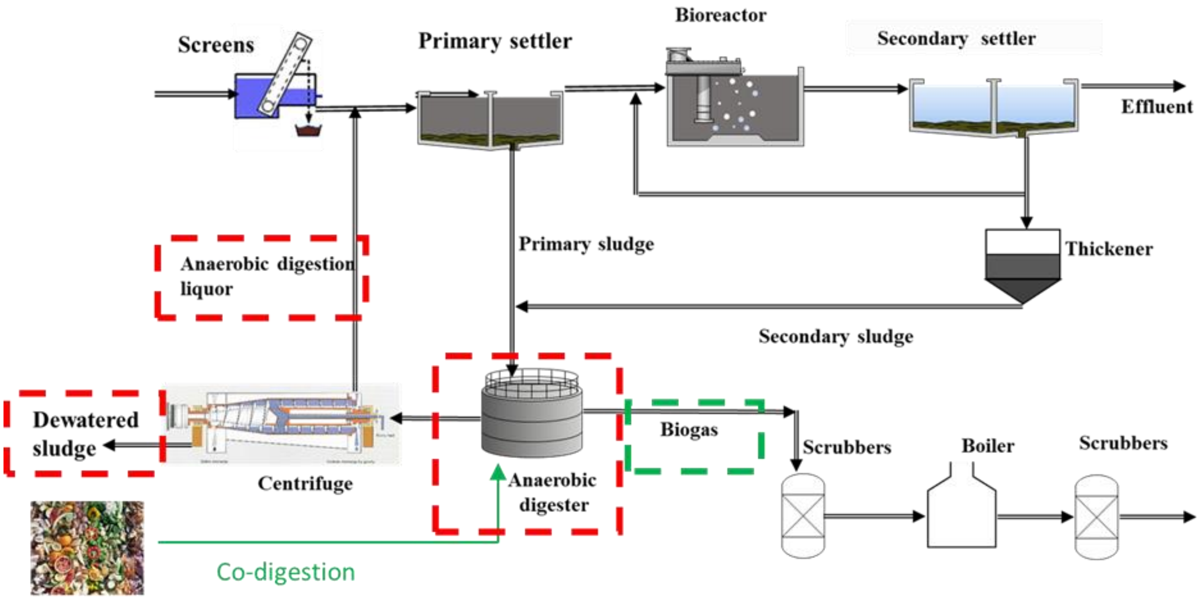


Figure 2 Schematic of municipal wastewater treatment plant importing external wastes for anaerobic co-digestion.

The dewatered sludge produced at a municipal WWTP is called biosolids and in some jurisdictions there are existing regulatory pathways that enable beneficial reuse of this material as an organic fertilizer via land application. Land application of biosolids is strictly regulated and the requirements vary between jurisdictions. In QLD, Australia, the requirements for land application of biosolids are described in Biosolids End of Waste Code (ENEW07359617). The code covers a stability requirement, summarized in Table 1 and limits on allowable contaminants, summarized in Table 2. A key aspect of the stability requirement is the vector attraction reduction requirement. The test for vector attraction depends in the treatment process applied at the WWTP, for biosolids generated from an AD process, the must have no more than 17% additional volatile solids reduction (AVSR) when incubated under anaerobic conditions in a bench scale reactor for an additional 40 days at 35-37° C.

FW and FIW is not expected to contain metal contaminants at levels that would impact the contaminant grade of the biosolids and is therefore unlikely to impact reuse under this criterion, under the current EoW code. However, FW and FIW may contain elevated levels of plastics and microplastics (i.e. from packaging), these plastic components are not regulated within the current EoW for biosolid but are regulated within a separate EoW code for digestate (EOWC010001054), suggesting the plastic content of biosolid will be regulated in the future and represents a future risk.

The AVSR threshold can be a key limiting factor for co-digestion applications and will be a focus of analysis in this project. When a co-substrate is added to an existing digester, the organic loading rate (OLR) of the digester generally increases. While this increased OLR can greatly enhance biogas production, it also decreases the hydraulic retention time (HRT). This can be problematic for continuous digesters close to their design loads because the shortened HRT reduces the time for degradation and microbial growth to occur and can result in a biosolids product that has not fully degraded and does not meet the AVSR threshold. Accordingly, wastes of high organic strength and low volume are often targeted, as a small increase in volumetric loading can considerably increase the OLR of the digester, leading to enhanced biogas production.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Table 1 Biosolids Stabilisation Requirements as presented in Table 4 of ENEW07359617

Pathogen Reduction Process	Vector Attraction Reduction Requirements
Stabilisation Grade A	
Biosolids have been treated using one of the following methods: 1. Thermally treated biosolids a) **Biosolids** > 7% solids with temperature at least 50° Celsius. The equation for the time-temperature requirement is: D= (131,700,000)/ ($10^{0.1400t}$), where D = time required in days, t = temperature in degrees Celsius. This option includes pasteurisation at 70°C for 30 mins; b) **Biosolids** > 7% solids. This option includes **composting** at 55°C for 3 consecutive days. c) **Biosolids** > 7% solids that are small particles heated by contact with either warmed gases or an immiscible liquid. The temperature should be at least 50°C for at least 15 seconds using the equation above. This option includes **biosolids** in contact with a hot gas stream in a rotary drier or **biosolids** dried in a multiple-effect evaporator system. d) **Biosolids** < 7% solids and less than 30 minutes contact time. Use equation 1 for contact times > 15 seconds and < 30 minutes. e) **Biosolids** < 7% solids and > 30 minutes contact time at 50° C or higher use equation (2) below: D = (50,070 000) / ($10^{0.1400t}$) This option includes thermophilic **aerobic digestion**. 2. High pH—high temperature process The pH of the **biosolids** product is to be raised to greater than or equal to pH 12 and remain above pH 12 for 72 hours. During at least 12 hours of the 72-hour period, temperature of the **biosolids** product must be greater than 52°C. After 72 hours **biosolids** product must be air dried to a solids content of more than 50%. 3. **Biosolids** from unknown processes For **biosolids** where the history of processing is not known, the product will be subject to a program of testing for the microbiological parameters contained in Table 2.	1. Treatment in an engineered system, operating within its design envelope, able to achieve the relevant metrics through either validated mathematical simulation, or physical testing[a]. 2. **Anaerobically digested biosolids** must have no more than 17% further volatile solids reduction when incubated under anaerobic conditions in a bench scale reactor for an additional 40 days at 35-37° C. 3. Aerobically digested **biosolids** must have no more than 15% further volatile solids reduction when incubated under aerobic conditions in a bench scale reactor for an additional 30 days at 20°C. 4. As an alternative to requirement 3, specific oxygen uptake rate for **biosolids** treated by an aerobic process have been less than 1.5 mg 02/hour/g total solids at 20°C.[b] 5. The pH value of the **biosolids** have been raised to 12 and without the addition of further alkali shall remain at 12 or higher for two hours and then at 11.5 or higher for an additional 22 hours. 6. For **biosolids** which contain stabilised solids only, the proportion of dry solids must be at least 75%. 7. For **biosolids** which contain unstabilised solids generated in a primary wastewater treatment process the proportion of dry solids have been at least 90%. 8. **Biosolids** have been treated in an aerobic process for at least 14 days. During that time, the temperature of the **biosolids** have been >40°C and the average temperature >45° C. This option relates primarily to composting as a stabilization process for biosolids with the feed being unstabilised solids.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Table 2 Biosolids Contaminant Thresholds as presented in Table 3 of ENEW07359617

Quality characteristic	Contaminant limits (dry mass) in mg/kg*		
	Grade A	Grade B	Grade C
Arsenic	20	20	20
Cadmium	3	5	20
Chromium (total)	100	250	500
Copper	150	375	2000
Lead	150	150	420
Mercury	1	4	15
Nickel	60	125	270
Selenium	5	8	50
Zinc	300	700	2500
Per and poly-fluoroalkyl substances (PFAS)	Monitoring required	Monitoring required	Monitoring required
Total Organic Fluorine (extractable)	Monitoring required	Monitoring required	Monitoring required
DDT/DDD/DDE	0.5	0.5	1.00
Aldrin	0.02	0.2	0.5
Dieldrin	0.02	0.2	0.5
Chlordane	0.02	0.2	0.5
Heptachlor	0.02	0.2	0.5
HCB	0.02	0.2	0.5
Lindane	0.02	0.2	0.5
BHC	0.02	0.2	0.5
PCBs	Not detected**	0.3	1.00

Notes:
* Contaminant limits are NOT mean values. Refer to Schedule 2 of the **NSW Biosolids Guidelines**.
**Not detected at a limit of detection of 0.1 mg/kg.

1.2.3 Feedstock Selection

Co-substrates are available from a broad range of industries that generate organic wastes including many sources of food waste and food industry waste. The physical, chemical and biological properties of these different waste streams can be very different, impacting both the compatibility of these waste streams with existing AD plants and the economics of treatment. Figure 3 is an example of energy revenue verses the cost of managing co-digestion residues for a range of waste streams being considered for import to a municipal WWTP. In the case of macerated solid food waste, the energy revenue was estimated at $50/wet ton imported, while the cost of residue management was approximately $40. This demonstrates that import of SFW to a WWTP may be profitable, but that process performance and local economic factors are likely important.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

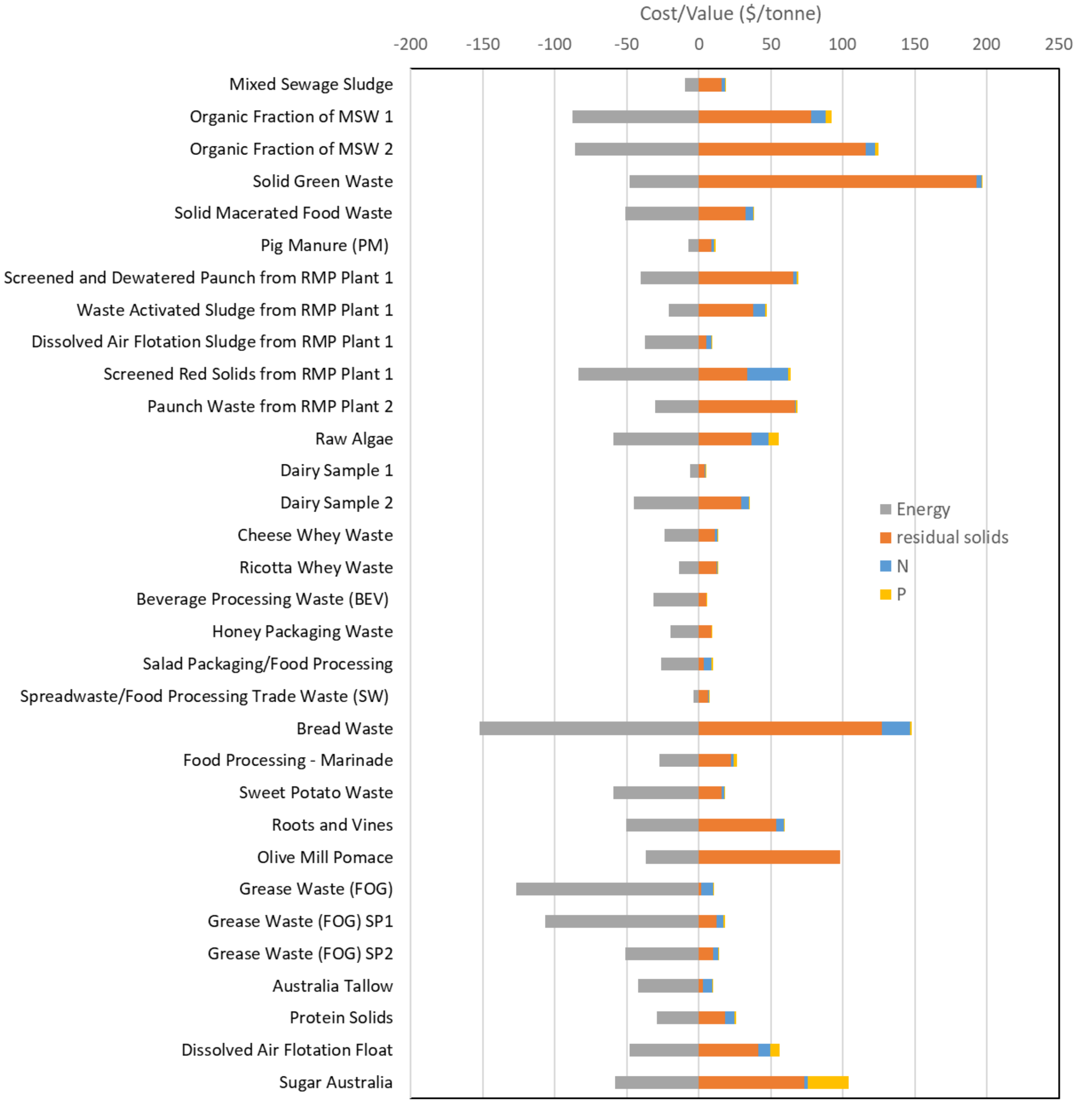


Figure 3 Example of energy revenue versus residue treatment costs for a range of co-substrates being considered for import to a municipal WWTP adapted from (Jensen and Tait, 2018)

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Importantly, previous research has demonstrated that the performance and the economics of co-digestion is impacted by both the substrate type and the loading rate of that substrate. Jensen and Tait (2018) reported the operation of continuous lab-scale anaerobic digesters receiving a base of mixed sewage sludge and a model co-substrate that was either a carbohydrate (cellulose), protein (gelatin) or a lipid (oleic acid), the co-substrates were added at loading rates ranging from 50% of the organic load, up to 125% of the organic load, with example results summarised in Table 3 and Table 4. The results of Jensen and Tait (2018) showed that methane production could be enhanced over 105% in a stable continuous process, but that substrate composition was critical to economic viability. Lipid based substrates were significantly more economical than carbohydrate-based substrates, which were more economical than protein-based substrates. While the processes were stable, in terms of biological indicators, the work showed that the conversion rates of the co-substrates decreased as organic load increased, resulted in reduced methane per ton, increase residual solids and diminished economic performance. This work highlights the need to consider both substrate type and import rate when assessing the viability of co-digestion processes. The work of Jensen and Tait (2018) was based on model co-substrates and needs to be validated using more complex real world waste streams.

Table 3 Economics for 1 ML digester with Co-digestion at 50% sludge OLR (Jensen and Tait, 2018)

Substrate	Sludge (40 ton/d) (1 ton/d dry)	Carbs (0.75 ton/d)	Proteins (0.5 ton/d)	Lipids (0.25 ton/d)
Methane ($/day)	135	275	247	271
Solids ($/day)	-$250	-$285	-$285	-$270
TAN ($/day)	-$88	-$65	-$370	-$83
Total ($/day)	-$203	-$75	-$408	-$82
Total Benefit ($/day)	-	+$128	-$205	+$121
Benefit per ton ($/ton)	-	+$170	-$410	+$484

Table 4 Economics for 1 ML digester with Co-digestion at 100% sludge OLR (Jensen and Tait, 2018)

Substrate	Sludge (40 ton/d) (1 ton/d dry)	Carbs (1.5 ton/d)	Proteins (1 ton/d)	Lipids (0.5 ton/d)
Methane ($/day)	156	310	277	344
Solids ($/day)	-$272	-$346	-$333	-$310
TAN ($/day)	-$80	-$36	-$635	-$68
Total ($/day)	-$196	-$72	-$691	-$34
Total Benefit ($/day)	**-**	+$124	-$495	+$162
Benefit per ton ($/ton)	**-**	+$83	-$495	+$324

1.3 Project Objectives

The project delivers translational research built on extensive fundamental knowledge. In addition to technical outcomes, this project will adopt well-proven strategies to the implementation of advanced anaerobic digestion technologies for industry-specific challenges. Project partners provide extensive connections to food and food processing wastes from existing trade waste customers, with access to new customers and sources of food waste developed through the CRC. Cases studies, modelling tools and the co-digestion manual will be used to identify suitable material for full-scale application and project outcomes are expected to be applied through the project partners within the life of the project.

The project will guide ongoing full-scale anaerobic co-digestion at the host site providing tangible economic and environmental benefits, as well as being directly transferable from the host site to broader industry. Knowledge from the project will broaden accepted process operating envelopes and promote acceptance of new food industry trade wastes as feed stocks for energy recovery. The project will promote full-scale application of co-digestion by guiding mixture selection based on individual constraints of each installation, and will significantly de-risk co-digestion through:

- Detailed understanding of materials handling and infrastructure requirements for successful co-digestion
- Understanding of materials handling and contamination challenges for food wastes.
- Understanding impact of co-digestion on secondary properties such as centrate and biosolids cake quality and volumes – thereby de-risking co-digestion economics.
- Understanding impact of upstream pre-treatment or process additives on co-digestion capacity – thereby aiding future planning and capacity planning during population growth.
- Multiple successful case-studies of co-digestion at demonstration scale of food waste in various WWTP scenarios
- Predictive model for degradation rates of co-substrates based on general composition metrics and correcting for key process conditions (e.g. temperature);
- A manual containing substrate screening tools, substrate mixture ratios, co-digestion dosage and control strategies and troubleshooting
- Significant uptake of co-digestion and development of links around anaerobic co-digestion, especially between organic waste source industries and wastewater utility firms.
- Report on Technoeconomic evaluations.
- Development of site-specific business case.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

2. Methodology

2.1 Analytical Methods

2.1.1 Measurement of Composition

Table 5 provides a summary of analytical methods used in this project. For measurement of soluble compounds including soluble chemical oxygen demand (COD), Total ammonical nitrogen (TAN) and phosphate phosphorus (PO_4-P), samples were centrifuged (5 min at 4,000 rpm) and filtered through a syringe filter (0.45 µm PES membrane) prior to analysis. For total COD (tCOD) and total nutrients and metals, samples were analysed as collected. Where required, samples were diluted with mill-Q water.

Table 5: Analytical Methods used to measure waste composition

Analysis	Description
Biogas	Biogas composition (N_2, H_2, CH_4 and CO_2) to be determined by gas chromatography using a Shimadzu GC-2014 equipped with a HAYESEP Q 80/100 packed column and a thermal conductivity detector (Shimadzu, Japan) using Argon as carrier gas.
TS, VS, Ash	Total solids (TS), Volatile Solids (VS) and ash content are measured according to Standard method 2540G of the American Public Health Association (APHA, 2012).
pH	Benchtop pH electrode and meter (Thermo Fisher Scientific).
Chemical Oxygen demand (COD)	Estimates the organic content of a sample. Also an order of magnitude estimate of chemical energy present in the sample (i.e. the energy released by each gCOD converted to CO_2 and H_2O by being chemically oxidised). Chemical oxygen demand (COD) was measured using Merck Spectroquant® cell determinations and a SQ 118 Photometer (Merck, Germany). Total and soluble fractions are measured.
Alkalinity	Measured by titrating a volume of sample with HCl to end points of pH 5.7 and pH 4.3. Partial alkalinity was determined using the pH 5.7 endpoint and represents alkalinity contributed by hydroxides, ammonia, carbonate and bicarbonate. Intermediate alkalinity was determined as the difference between alkalinity to pH 5.7 and alkalinity to pH 4.3 and represents the contribution by organic acids. The alkalinity ratio (α) is defined as the ratio of partial alkalinity to intermediate alkalinity; with ratios <0.3 representing a healthy process (Ripley et al., 1986).
VFA and Alcohols	Volatile fatty acids (C2 to C6) and alcohols (ethanol, propanol, butanol) in samples are determined by gas chromatography using a flame ionisation detector (FID) and a polar capillary column (DB-FFAP).
Fats, Oil and Grease	Merck Photometric tests NOTE – testing as required
NH_4-N* & PO_4-P*	Flow Injection Analysis (Lachat Instruments).
TKN & TP	Sample is first digested with sulfuric acid, potassium sulphate and copper sulphate catalyst in a block digester; then analysed via FIA (Lachat Instruments).

2.1.2 Biosolids properties and End of Waste Code Compliance

This section describes methods used to assess the impact of co-digestion on Biosolids volume, composition and quality from co-digestion, focusing on parameters described in Biosolids EoW and select emerging contaminants (i.e heavy metals). A summary of analytical methods utilised to assess biosolids properties and compliance with Queensland End of Waste requirements is shown in Table 6, in general this analysis will be completed once per SRT. This analysis considers both ENEW07359617, which is the current End of Waste code applicable to biosolids produced at a municipal Wastewater treatment plant (WWTP) and EOWC010001054 which is an End of Waste code applicable to digestate from AD processes that do not contain municipal sludge.

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Table 6: Summary of analytical methods used to assess compliance with ENEW07359617 and/or EOWC010001054

Analysis	Description
Additional Volatile Solids Reduction (AVSR)	The procedure used in AVSR tests is based on the procedure recommended by Farrell et al 1996 as follows (Farrell et al., 1996): Tests commenced within 4-6 hours of sample collection. Fifteen (15) representative subsamples of approximately 70 mL are collected from each digester sample. Five (5) subsamples are randomly selected for analysis of total solids and volatile solids. The remaining ten (10) samples are placed in separate glass serum vials, the headspace of each vial is flushed with high purity nitrogen (99.9%) for 3 min. Each vial is then sealed with a butyl rubber stopper and aluminum crimp seal and stored in a temperature controlled incubator at 37°C (±1°C). Gas was released from each vial every 2-3 days, but is not measured during release. Five (5) vials are randomly selected after 20 days and opened for analysis of total solids and volatile solids. The remaining five (5) vials are opened after 40 days for analysis of total solids and volatile solids.
Metals	ICP-OES (Agilent Technologies); targeting select isotopes of Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Se, & Zn.
Dewaterability – Centrifuge Method	Centrifuge dewaterability is assessed using a centrifuge method developed in conjunction with Bucknell University. Initially, 100 g of conditioned solids is free drained through belt filter fabric for 1 min to establish a filter cake. The cake was scraped into a custom designed belt filter cup and centrifuged as follows: 1. 200 times gravity for 2 min. 2. 500 times gravity for 2 min. 3. 2500 times gravity for 10 min. The cake is mixed and redistributed across the filter cloth between each centrifuge cycle. After centrifuging, the moisture/solids content of the cake is measured according to Standard Methods procedure 2540G (Franson et al., 2005).
Dewaterability – Thermogravimetric Method	Thermogravimetric dewaterability analysis is done according to Kopp and Dichtl (Kopp and Dichtl, 2000). The Kopp and Dichtl (2000) methodology measures' drying rate in a controlled situation and determines the free and interstitial water based on the inflection points of a drying curve. The free moisture limit can be correlated with performance on centrifugal and press dewatering equipment, while the capillary limit indicates the expected performance in thermal dryers. After drying, the moisture/solids content of the cake is measured according to Standard Methods procedure 2540G (Franson et al., 2005).

2.1.3 Characterization of Process Performance

In many applications the economic viability of AD is more sensitive to solids destruction and the level of solids stabilization than biogas production. Therefore, total solids (TS) and volatile solids (VS) are common parameters to characterize the feedstock prior to anaerobic digestion and to characterize the performance of the anaerobic digestion process. Specifically, VS destruction is a primary

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

measure of process performance. There are three common ways to calculate VS destruction: (i) mass-balance VS destruction; (ii) Van Kleeck VS destruction; and (iii) apparent VS destruction on gas flow, which relies on the principle that organic matter destroyed must be converted to biogas. Calculation procedures for monitoring VS destruction in AD processes are shown below.

Mass Balance VS destruction:

$$VSD_{MB} = \frac{VS_{conc,in} - VS_{conc,out}}{VS_{conc,in}}$$ **Equation 1**

$$VSD_{VK} = \frac{VS_{frac,in} - VS_{frac,out}}{VS_{frac,in} - (VS_{frac,in} \cdot VS_{frac,out})}$$ **Equation 2**

Where VS_{conc} is concentration of organics as measured by the volatile solids method (g L^{-1}), $VS_{frac}$is fraction of total solids that is volatile (VS_{conc}/TS_{conc}) and subscript in and out indicate concentrations in the inlet and outlet streams

2.2 Laboratory Assessments of Methane Energy Potential

2.2.1 Batch Biochemical Methane Potential (BMP) Testing

Batch Biochemical Methane Potential (BMP) tests are a routine laboratory test used to determine the anaerobic biodegradability of a test materials (the substrate). BMP tests were conducted following the protocol outlined (Angelidaki et al., 2009a), using glass serum bottles incubated at mesophilic conditions (37 ± 1 °C). The working volumes of the serum bottles was 100 mL, 200 mL or 300 mL as required by the experiment). All tests examining the mono-digestion of a substrate used an inoculum-to-substrate ratio (ISR) of 2.5 on a volatile solids (VS) basis. For tests examining co-digestion, the inoculum-to-base substrate (PS and TWAS) ratio was 2.5 (VS basis, co-substrate was then added as additional substrate which reduced the overall ISR. Experimental designs that increased substrate load were selected to explore process overload risks that develop from increasing the substrate throughput into an established process.

Before sealing, the bottle headspace was purged with 99.99% nitrogen gas for 30 seconds at a 4 L·min^{-1} flow rate to establish an anaerobic headspace. The bottles were sealed with rubber stoppers and aluminium crimp caps, incubated in a temperature-controlled chamber at 37 ± 1 °C, and mixed manually before each sampling event. Inoculum-only blanks were included to account for baseline methane production. Positive controls were conducted for all experiments with microcrystalline cellulose was used as a reference substrate. All tests, including blanks and positive controls, were tested in triplicate to assess variability and reproducibility, and all error bars indicate confidence intervals (CI) of 95% CI in the average of the triplicate. An example result from a BMP test is shown in Figure 5.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Figure 4 Example of batch biochemical methane potential assay (Left) and stored in a temperature-controlled incubator during testing (right)

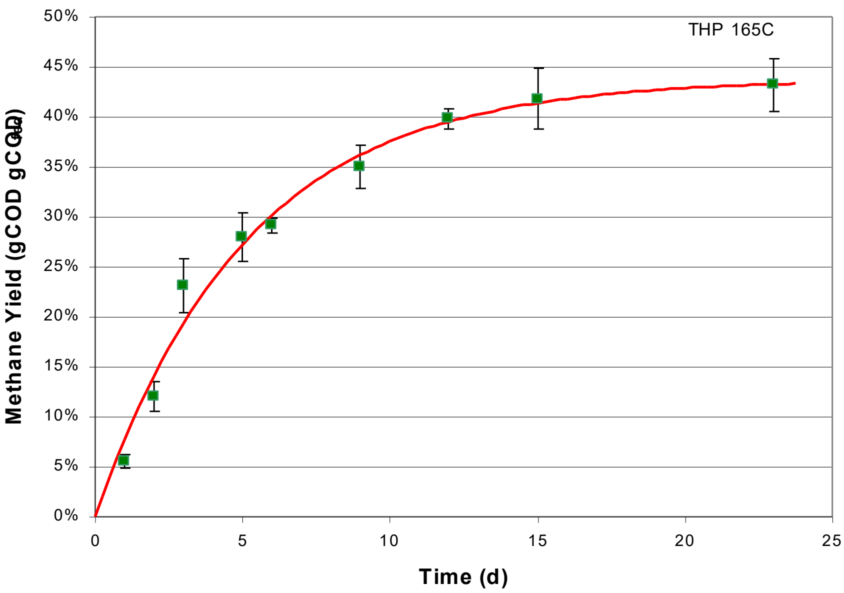


Figure 5 Example output from biological methane potential (BMP) test. Error bars indicate 95% confidence errors from triplicate batches. The line indicates the model used to return key parameters.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

2.2.2 Data Analysis and Modelling

Parameters from BMP testing are used in desktop analysis to determine the feasibility of anaerobic digestion technology and are used in anaerobic digestion process designs. Important outputs from a BMP test include:

- Biochemical methane potential (B_0) - representing the final methane yield that can be achieved through anaerobic digestion of the trade waste under ideal conditions. Expressed at L CH_4/kg VS added.
- Degradable fraction (f_d) – representing the fraction of organic material in the waste that can be converted to methane under ideal conditions. Degradable fraction is typically based on the fraction of COD converted to methane, but may be used to estimate volatile solids destruction, nitrogen mobilisation and phosphorus mobilisation during AD.
- Apparent Hydrolysis rate constant (k_{hyd}) – representing the speed of anaerobic digestion at mesophilic conditions. The hydrolysis rate constant is used to determine reactor sizing to enable complete conversion of a waste, or to estimate the extent of conversion based on an existing reactor size (Angelidaki et al., 2009b, Holliger et al., 2016, Lesteur et al., 2010).

Degradability parameters were determined using a simple first order kinetic model (Equation 3) fitted using model-based software (Aquasim 2.1d). as expressed as:

$$S_{CH4} = B_0\left(1 - e^{-k_{hyd}.t}\right) \qquad \textbf{Equation 3}$$

As a microbial process, AD can be impacted by a range of unfavourable environmental conditions, or compounds with inhibitory or toxic effects. A lag time (days) was implemented into the first order model as a method of accounting for inhibition in the BMP tests. The fitted lag time does not indicate the inhibition threshold of a compound, but can be useful in comparing the relative impact of inhibition. For example, a longer lag time indicates a longer adjustment period for the microbial community to overcome inhibition and therefore suggests stronger inhibition. Data collected during the lag period was not included in the model fits for B_0 and k_{hyd}.

2.3 Anaerobic Digestion Pilot Facility

2.3.1 Pilot Design

This project utilized the Anaerobic Co-digestion demonstration plant currently located at a municipal wastewater treatment plant in Southeast Queensland. The demonstration facility (Figure 2) includes two independent AD pilot skids. Each pilot skid contains:

- Feed tank for mixing waste streams and addition of dose chemicals (i.e. Fe).
- Anaerobic digester (2400L), mixed by recirculating biogas through gas lances.
- Post-AD conditioning tank (700 L) with capability for MHL chemical dosing.
- A process control system.

A summary of start-up conditions in shown in Table 7, during the start-up phase sludge loading was reduced to approximately 50% of the sludge load expected during steady operation.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

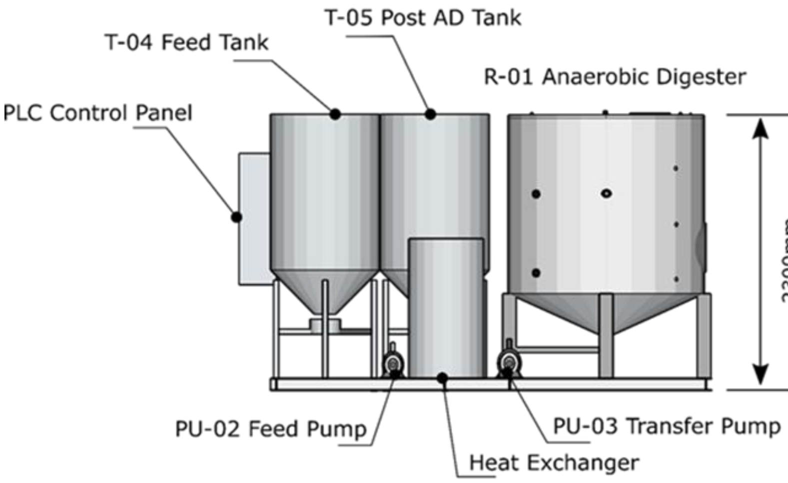


Figure 6. Schematic of Advanced Anaerobic Digestion Demonstration Skid, incorporating a 3000L anaerobic digestion vessel and supporting equipment.

Table 7: Summary of Operating Parameters during Start-up Phase

Parameter	Pilot 1	Pilot 2
Temperature (°C)	38	38
Mixing Regime	continuous	continuous
AD operating Volume (L)	2,400	2,400
Sludge RT (d)	40	40
Sludge Load (L/d)	120	120
Sludge OLR (base) (kgCOD/m^3/d)	1.5	1.5
Sludge feeds per day (d^{-1})	1	1
Sludge volume per feed (L)	120	120
Sludge feeds per day (d^{-1})	1	1

.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

2.3.2 *Process Performance and Stability*

This section describes methods used to assess the impact of co-digestion on process stability, gas production rates, biosolids properties and centrate properties. Process performance and stability was assessed using both online measurements and through collection of samples for offline analysis (Table 8). Biogas flowrate was a key online parameter which enabled the project to measure and report the dynamic response in biogas production rates when co-substrate was applied. Flowrates, temperatures, headspace pressures, tank levels and pH were also measured online, largely to ensure process equipment was functioning correctly.

Other than biogas production dynamics and pH, the assessment of process performance was based on samples collected from the feed tanks (primary sludge, activated sludge, trade waste, mixed feed), anaerobic digester bulk volume and the post-AD conditioning tank bulk volume; and measured offline. These samples were collected and assessed 2-3 times per week using analytical methods shown in Table 6. Key outputs used to assess process performance included: COD destruction, VS destruction (via mass balance, Van Kleeck and gas flow), biogas/methane production and nutrient mobilisation (N and P). Additionally, lab scale BMP testing was done on feed samples to benchmark the performance of the pilot plant.

Table 8: Summary of Pilot Monitoring and Analytical Plan

Online Parameters (Continuous Monitoring)					
	Sludge	**TW**	**Digester**	**Post -AD**	**Biogas**
Flow (m^3/d)	X	X	X	X	X
Temperature			X		
Pressure			X		X
pH				X	
Offline Parameters (2-3 per week)					
COD	X	X	X	X	
TS	X	X	X	X	
VS	X	X	X	X	
Organic Acids	X	X	X	X	
Nutrient (TKN/P)	X	X	X	X	
Soluble Nutrients	X	X	X	X	
Alkalinity			X	X	
CH_4					X
CO_2					X
H_2					X

2.4 Full-scale Model Development

A continuous mixed tank (CSTR) model was developed to adapt results from batch laboratory tests to a continuous process configuration and make predictions about process performance. These predictions were then compared to pilot-plant data and in some cases full-scale data to validate experimental outcomes. A conceptual representation of the CSTR model is shown in Figure 7,

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

the model inputs include: i) the feed rate and kinetic behaviour of base substrates (composed of PS and TWAS), ii) the feed rate and kinetic behaviour of co-substrate(s), which can be applied individually, and iii) the digester working volume. The model outputs include: i) the steady state biogas production, ii) the volatile solids reduction and corresponding residual solids mass, iii) the residual degradable solids and the corresponding impact on AVSR and iv) the mass of nutrient mobilised and recycled in the centrate.

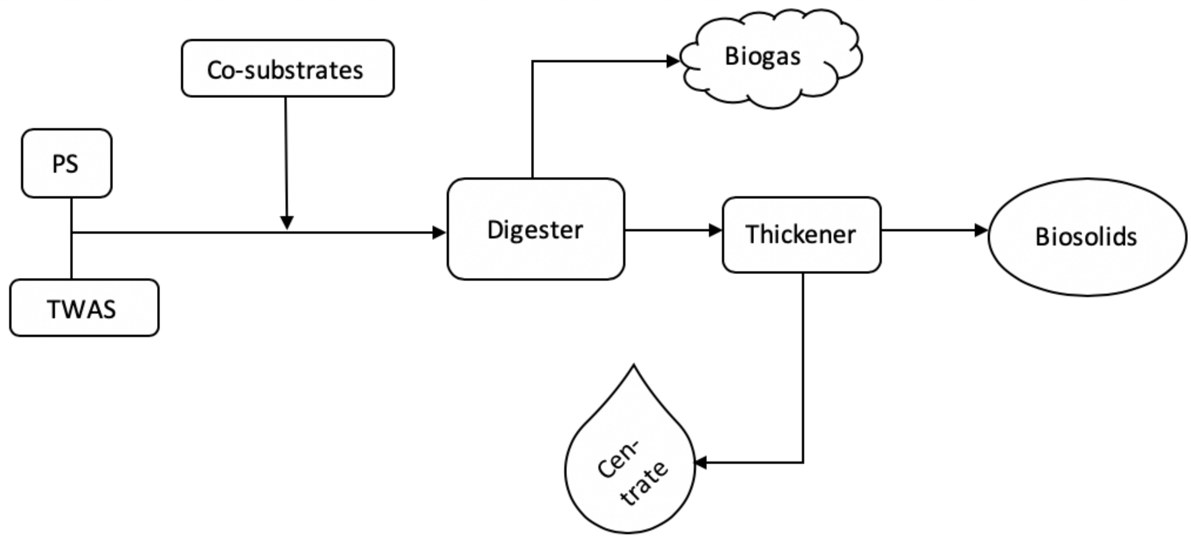


Figure 7 Conceptual Mixed Tank reactor model (CSTR model).

For the implementation of this model, the following simplifications and assumptions were necessary.

- The full-scale digester can be modelled as a CSTR in steady-state conditions, meaning that inflow equals out flow and that the following equation applies.

  $$S_t = \frac{S_0}{(1+k_{hyd}.SRT)} \qquad \textbf{Equation 4}$$

  where S_t is the concentration of substrate within the vessel, S_0 is the initial concentration of substrate, k_{hyd} is the apparent hydrolysis rate constant and SRT is the solids retention time (in days).

- The characteristics of Primary Sludge (PS) and Thickened Waste Activated Sludge (TWAS) are constant and these streams are produced in consistent volumes.
- The characteristics of food industry wastes are constant and added in a manner where the process can operate under steady-state conditions, at a constant organic loading rate.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

- No synergies or antagonisms evolve during the co-digestion. The different substrates are digested independently. The degradability f_d and hydrolysis rate constant k_{hyd} of the co-digestion correspond to the sum of the mono-digestion multiplied by the percental organic loading contribution of each to the co-digestion.
- The thickener has an efficiency of 95%, meaning that 5% of undigested solids remain in the centrate and are returned to the nutrient removal bioreactors. The thickener achieves a TS concentration of 25% in the thickened cake.
- Organic nitrogen and organic phosphorous are digested in the same ratio as volatile solids. The digested N and P are converted to ammonium and phosphate and are retained in the centrate stream.
- The residual degradable fraction was determined from balancing the initial degradable fraction and the material consumed according to Equation 4. The ASVR as estimated by assuming any degradable material in the digester effluent continues to degrade at 0.08 day^{-1} for a period of 40 days (based on average decay rate of AD effluent collected from the host plant).

2.5 Approach to Defining Process Limits

Identification of process operating limits and analysis of process failure scenarios are strategies that can be used to understand the risk of co-digestion and manage process operation. Co-digestion will impact three major streams when applied at a municipal WWTP (represented in Figure 2), these streams are the centrate recycled to the nutrient removal bioreactors, the final biosolids product and the biogas product. Within these streams, the following factors were identified as potential process limits for evaluation within the project:

1. Digestate that exceeds requirements stated with the EoW code for Biosolids:
    a. Steady state AVSR exceeds 17% during 40 days additional storage
    b. Steady state indicator contaminants that exceed EoW code
2. Mass of Soluble organics in side-stream centrate:
    a. Soluble organics are intermediates of AD. Accumulation can be used to identify a biological limit for methanogenesis.
    b. Mass of soluble organics returned to biological nutrient removal is lost revenue and may represent an upset failure risk (i.e. for annamox).
3. Mass of Nitrogen in side-stream centrate: This represents the mass of nitrogen returned to biological nutrient removal and may exceed an equipment bottleneck.
4. Mass of Solids in AD effluent: Solids handling and utilisation is a common equipment bottleneck and can be used to identify a process limit.
5. Maximum short term biogas production rate: Gas handling and utilisation is a common equipment bottleneck and can be used to identify a process limit.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

2.6 Economic Assessment of Co-digestion

The conceptual mixed tank model described in Section 2.4 was used to predict changes in biogas output, biosolids production and nutrient load in the centrate. These factors represent key economic impacts from AcoD at a municipal WWTP. Table 9 is a summary of the economic factors used to assess the impact of co-digestion in this project, these costs are based on discussions from multiple industry sources and are not based on the specific costs incurred at the host site (for commercial-in-confidence reasons). Biogas is the only revenue stream considered within the analysis in this project, however it is common practice for wastewater treatment plant operators to apply a gate fee when receiving and processing external waste streams – gate fees were not considered in this report for commercial in confidence reasons.

Table 9: Cost factors used in Economic Assessment of Anaerobic Co-digestion

Cost Factor	Cost	Unit
Biogas Energy Revenue	200	$ per MWh
	305	$ per ton degradable COD[1]
Biosolids Disposal Cost	150	$ per wet ton
	570	$ per ton non-degradable solids[2]
Nitrogen Removal Cost	2	$ per kg Nitrogen in Centrate
Phosphorus Removal Cost	2	$ per kg Phosphorus in Centrate

1. 1 ton degradable COD converts to 350 m^3 methane, which produces 13.5GJ heat or 1.5 MWh power @ 40% conversion efficiency
2. 1 ton non-degradable solids produces 3.8 ton of waste biosolid @ 95% capture and 25% dewaterability

The Australian Carbon Credit Unit (ACCU) scheme may also apply where the FIWs used in co-digestion have been redirected from landfill (Source Separated Organic Waste Method), however ACCUs are subject to application and approval and have not been applied in this report.

2.7 Emissions Impact from Co-digestion

The impact of co-digestion on greenhouse gas emissions was assessed using methods described in "Australian National Greenhouse Accounts Factors" (DCCEEW, 2025). A summary of emissions factors used is presented in Table 10. The conceptual mixed tank model described in Section 2.4 was used to generate simulation data for the assessment. The CSTR model predicted biogas production, biosolids production and nutrient load in the centrate. These factors were then used to estimate the production of renewable energy at the WWTP. Production of renewable energy assumed the calorific value of methane was 38 MJ/m^3 (normalised to 0°C and 1 atm), the electrical efficiency of co-generation was estimated at 40% of combustion heat. When conducting the energy balance, an energy cost of 10 kWh/t was applied for biosolids dewatering (based on 40 kWh/dry ton for centrifuge dewatering) and an aeration energy cost of 2.5 kWh/kgN was applied for nitrogen recycled in the centrate.

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Table 10: Emissions factors used to assess the impact of Anaerobic Co-digestion

Emission Factor	Cost	Unit
Scope 1 Emissions from Energy Production using Biogas	6.43	kg CO_2-e per GJ
Scope 1 Emissions from Anaerobic Digestion of wastes	28	kg CO_2-e per ton
Scope 2 Savings from Reduction in Purchased Electricity (QLD)	0.67	kg CO_2-e per kW.h
Scope 3 Savings from Reduction in Purchased Electricity (QLD)	0.09	kg CO_2-e per kW.h
Scope 3 Emissions Avoided by Redirecting Waste from Landfill (SFW and GTW)	2100	kg CO_2-e per ton
Scope 3 Emissions Avoided by Redirecting Waste from Landfill (DMP and BEV)[1]	1050	kg CO_2-e per ton

1. Assumed at 50% the NGERS method for food waste emissions as the methane potential of DMP and BEV was ~50% that of SFW per fresh ton

3. Results

3.1 Evaluating the Energy Potential of Food Industry Wastes

3.1.1 Composition of Waste Streams

This section examines a selection of four food industry waste streams produced in Southeast Queensland to assess the suitability for co-digestion in a municipal wastewater treatment plant. Representative images of the Food Industry Wastes (FIW) are shown in Figure 8. The specific origin of the waste streams cannot be described for commercial reasons; however general descriptions include:

- BEV: Liquid Waste from a Beverage Processing facility.
- DMP: Liquid Waste from a Dairy/Milk Processing facility
- GTW: A waste slurry from commercial grease traps.
- SFW: A pre-consumer food waste (from large supermarket distribution centres) that has been de-packaged and macerated.

Figure 8 Food Industry Wastes (FIW) investigated in this project

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

The physical and chemical compositions of the waste streams were assessed based on 4 key areas:

a) Chemical Oxygen Demand – Chemical oxygen demand represents the energy potential of a substrate. Anaerobic co-digestion is generally applied to existing AD infrastructure, in this type of application reactor volumes are a fixed size. Adding co-substrates will generally increase the total volume of waste being treated in the reactor and this decreases retention time. Co-substrates with very high COD can be used to significantly increase organic loading to a reactor with only minor changes to volume loading and retention time. However, dosing of these substrates must be managed carefully to limit the risk of overload.
b) Solids Concentrations – solids concentration is linked to i) organic loading potential, where materials with higher solids can potentially achieve higher loading rates, ii) materials handling requirements, where materials with higher solids may be more difficult handle, transport and/or mix within the digester and iii) technology suitability, where co-substrates with very low solids are generally suited to different reactor technologies compared to co-substrates with very low solids. The fractionation between volatile solids and ash also provides an indication of inert material entering the digestion process. Ash will not contribute to AD and will either accumulate within the process or exit as residual solids. Therefore co-substrates with very low ash content are preferred.
c) COD to Nitrogen Concentration – Depending on the application, nitrogen represents a significant cost associated with importing wastes for co-digestion (i.e. where nitrogen is mobilised and must be removed prior to discharge of the centrate) or a value-add opportunity where nitrogen increases the fertilizer value of the centrate and/or solid digestate.
d) COD to Phosphorous Concentration – Depending on the application, phosphorous represents a significant cost associated with importing wastes for co-digestion (i.e. where phosphorous is mobilised and must be removed prior to discharge of the centrate) or a value-add opportunity where phosphorous increases the fertilizer value of the centrate and/or solid digestate.

Table 11 is a summary of food industry waste compositions, the composition of primary sludge and waste activated sludge currently managed at the wastewater treatment plant is included for comparison. All FIWs tested in this project contained higher concentrations of both solids and COD compared to the sewage sludge base substrate. Therefore, all potential co-substrates will have stronger impact on organic loading rate and a lesser impact of volume loading. GTW was the highest strength in terms of COD, with average COD values approximately 5x larger than sewage sludge, therefore GTW could be used to substantially increasing organic loading with little impact on volume. GTW also contained very high COD/N and COD/P ratios, therefore GTW could be used to substantially increase organic loading with little impact on N and P costs within the recycled centrate. However, the strength of GTW was also highly variable, with COD concentrations differing by up to 400% across tanker loads (91 g/L up to 375 g/L). This variability can lead to increased fluctuations in the organic loading to the digesters and may have considerable impacts on process performance, with additional risks of transient inhibition and delayed gas production at high tanker concentrations. GTW is largely a liquid waste stream and is not expected to pose any significant material handling challenges.

Macerated SFW was also a concentrated sources of organics at greater than 3x sewage sludge, however this material contained a much lower soluble fraction and materials handling may be more challenging. The COD/N ratio of SFW was significantly lower than other FIWs and only marginally higher than the sewage sludge base substrate, therefore nutrient management costs will be more

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

significant. SFW was only received at a single time point during the project, therefore variability between tanker loads could not be assessed. Interviews with operational staff indicate that the material may be highly variable, due to variations waste timings that result in different ratios of meat, dairy, fresh produce and baked goods within the mix.

DMP and BEV were moderately concentrated. These wastes generally contained high soluble fractions, suggesting high biodegradability and good materials handling characteristics, however the lower strength of these wastes suggests that limited increases in OLR can be achieved without exceeding the volume loading limits of existing digesters. The low strength may also increase the relative transport costs to import these co-substrates to site.

Table 11: Concentration of organics, solids and key nutrients in Waste Samples

Characteristic		TCOD g/kg	TS g/kg	VS g/kg	Ash g/kg	TKN as N mg/kg	TP as P mg/kg	COD/N	COD/P
Mixed Sewage sludge (MSS)	Average	63	49.6	38.3	11.3	2730	890	23.1	71
Primary Sludge (PS)	Min	51.3	23.2	17.4	3.9				
	Average	57.2	38.7	32.8	6.0	2400	360	23.8	159
	Max	61.6	68.1	59.2	8.9				
Waste Activated Sludge (WAS)	Min	51.6	45.5	35.0	7.7				
	Average	56.9	49.4	39.9	9.4	3200	1100	17.8	52
	Max	62.0	58.7	47.3	12.5				
Grease Trap Waste (GTW)	Min	90.8	38.0	35.1	2.5				
	Average	279.9	80.4	77.1	3.3	1200	160	233	1750
	Max	375.1	116.5	113.6	3.7				
Dairy/Milk Processing (DMP)	Min	40.9	12.7	12	0.7	148	160		
	Average	94.0	53.0	47.0	6.0	1290	650	72.9	145
	Max	139	85.2	69.2	36.6	2621	2120		
Beverage Processing (BEV)	Min	59.3	12.4	11.7	0.7	60	60		
	Average	103	50	47	2	980	340	105	303
	Max	199	96.7	87.7	9.1	5000	2230		
Solid Food Waste (SFW)	Average	203	165	150	15	5,340	1,100	38	185

Note: N/A denotes not assessed

3.1.2 Availability of Food Industry Wastes

Target waste imports are not shown for commercial reasons, however the breakdown of waste contributions at target import levels are:

- DMP: 9% of waste import volume and 5% of imported organic load (3% base load)
- BEV: 19% of waste import volume and 11.5% of imported organic load (7% base load)
- GTW: 19% of waste import volume and 28% of imported organic load (17% base load)
- SFW: 52% of waste import volume and 56% of imported organic load (34% based load)

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

At the time of this analysis, the WWTP was operating 5 commercial scale anaerobic digesters at a base retention time of 20 days and a base sludge load of 2.5 kgCOD/m^3/d; the WWTP has the potential to load imported wastes into a single anaerobic digester or can distribute the imported wastes relatively evenly across the 5 operational digesters. If the food industry waste import targets are achieved this would correspond to 300% of the base organic load if added to a single digester whilst also reducing the treatment time from 20 days to approximately 10.5 days – this scenario represents a substantial process failure risk. However if the wastes are distributed evenly across the digesters, the increase in organic load is reduced to 60% with the treatment time reducing from 20 days to 17 days and is consistent with levels achieved in long term lab-scale experiments (where organic load increases up to 125% were successful) (Jensen and Tait, 2018).

The waste loads received in 2023/24 are significantly lower than target levels. The breakdown of waste contributions in 2023/24 were:

- DMP from facility-1: 21.7% of waste import volume and 10.6% of import organic load (~1% base load)
- DMP from facility-2: 14.3% of waste import volume and 7.0% of import organic load (~1% base load)
- GTW: 64% of waste import volume and 82.4% of import organic load (10% base load)

At current FIW import levels, organic loading should not represent a process limit. The food waste load represents an organic load of 1.2 to 1.7 kgCOD/m^3/d if added to a single digester (50-70% increase in organic loading) or 0.25 to 0.35 kgCOD/m^3/d if distributed to the 5 operational digesters (10-14% increase in organic loading). The average volume of waste received was 40 m^3/d, as a long-term average this would reduce the treatment time to 17.3 days if added to a single digester and should not represent a process failure risk. If distributed across 5 operating digesters, the FIW imports would not have a significant impact on treatment time with no significant process risk.

3.1.3 Assessment of Biodegradability Parameters

Figure 9 shows methane production from food industry wastes in comparison to mixed sewage sludge, kinetic parameters estimated from modelling are presented in Table 12.

Table 12: Kinetic parameters estimated from model analysis of single substrate BMPs

Substrate	Lag (days)	Apparent hydrolysis Rate (k_{hyd}):	Degradable Fraction (fd)	Methane Potential (L/kgVS):	Methane Potential (m^3/wet ton):
Mixed Sludge	0	0.20 ± 0.04	0.46 ± 0.03	262 ± 14	10.0 ± 0.5
BEV	1.7 ± 0.6	0.24 ± 0.07	0.80 ± 0.02	617 ± 40	29 ± 2
DMP	0.4 ± 0.4	0.20 ± 0.04	1.02 ± 0.02	714 ± 28	33.6 ± 1.4
GTW	12 ± 0.4	0.18 ± 0.03	0.83 ± 0.02	685 ± 34	72 ± 4
SFW	0.2 ± 0.2	0.44 ± 0.07	0.89 ± 0.04	422 ± 12	64 ± 2

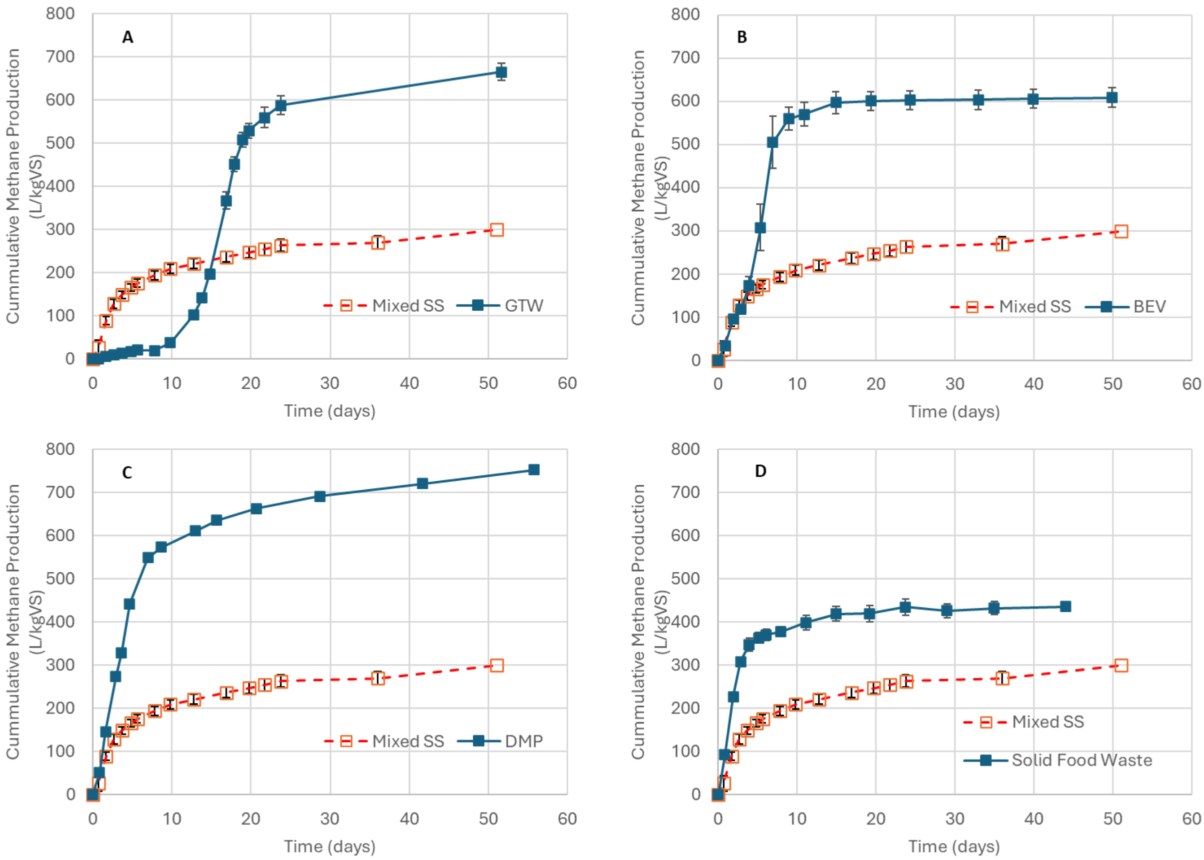


Figure 9 Cumulative methane production from Food Industry Wastes (FIW) during batch BMP tests

The methane production from FIWs ranged from 430 L/kgVS to over 700 L/kgVS. Importantly, the methane potential from all FIWs tested in the project was significantly higher than the 300 L/kgVS produced from mixed sewage sludge. GTW, DMP and BEV contained very high methane potentials, which is consistent with the high theoretical methane potential for the lipids, proteins and alcohols expected in these streams. DMP was also completely degradable and would produce no additional biosolids if sufficient treatment time is provided. GTW and BEV were highly degradable (~80%) and will likely result in some increase in residual biosolid. produce some residual solids. The methane potential of SFW was moderate at 430 L/kgVS, however this stream was highly degradable (~90%) and degraded very quickly in comparison to other streams. Results for SFW will be impacted by the ratio of food products being wasted on any given day and more work is required to establish this variability.

3.1.4 Modelled Degradation of Food Industry Wastes during Mono-digestion.

Figure 10 shows the predicted degradation behaviour for each co-substrate in a continuous mixed reactor as a function of treatment time. The curves in Figure 11 were developed using kinetic models from the batch BMP tests (Table 12) and importantly these results demonstrate that the co-substrates will not achieve complete degradation (of the degradable fractions) within the existing reactors at the partner site. For example, the methane potential of GTW was modelled at 685 L/kgVS, however the methane production predicted at the host site range from 536 L/kgVS (at the current SRT of 20 days) down to 516 L/kgVS (at an SRT of 17 days corresponding to the maximum volume load of co-substrates) and represents only 75-78% of theoretical energy recovered. DMP performs slightly better with recovery of 77 to 70% of theoretical methane, followed by BEV at 80-83%. SFW is expected to degrade most completely with 88 to 90% of theoretical methane recovered. The impact of incomplete degradation on process economics and process limit indicators (such as EoW compliance) is assessed in more detail in Section 3.4.

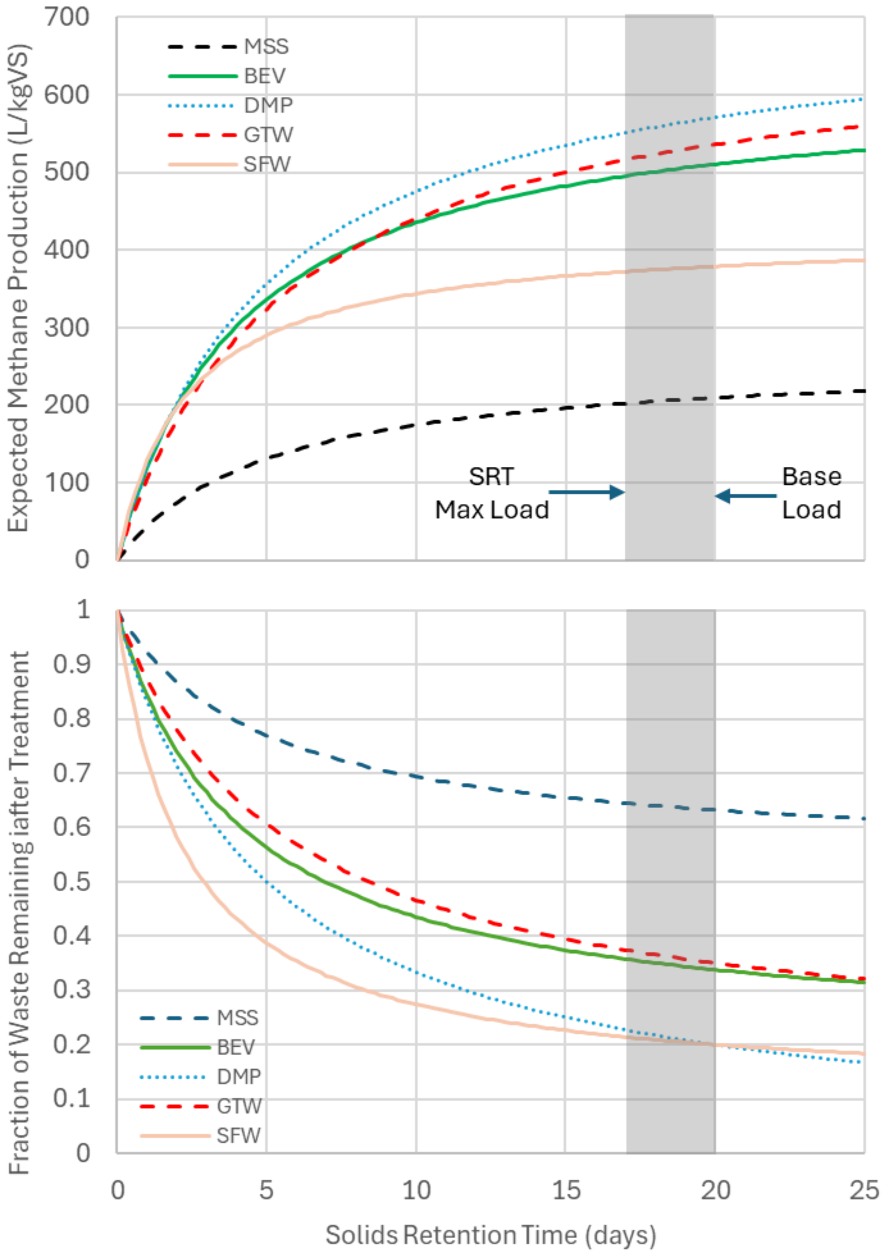


Figure 10. Prediction of degradation behaviour in mixed tank reactors as a function of treatment time, using kinetic models determined from BMP testing. Top: Predicted Methane production. Bottom: Fraction of waste remaining.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

3.2 Validation of Continuous Anaerobic Co-digestion at Pilot Scale

3.2.1 Experiment 1 – Assessing Current Operational Loads

3.2.1.1 Objective

Experiment 1 was designed to validate the performance of the AcoD at current operational loads and assess the impact of co-substrate dose regime (i.e. distributed load vs spike load) on process stability, gas production rates, biosolids and centrate properties. In the spiked dose strategy, the base load of sludge is added to the pilot in small doses across the day (4x per day). Co-substrate is added to the pilot in a large spike dose, provided independent of the sludge feed. The spiked dose strategy simulates a scenario where a waste tanker arrives on site and the imported waste is added directly to the process, without using an equalisation system to distribute the load over an extended period.

3.2.1.2 Pilot Operating and Loading Strategy

Table 13 is a summary of the operating parameters and co-substrate loading to each pilot during Experiment 1. The nominal sludge loading in Experiment 1 is based on 2.5 kgCOD/m^3.d. The co-substrate loading in Experiment 1 is designed to replicate the trade waste receival from 2023/24, with an even distribution across 5 operating full-scale AD. The additional volume load of the FIWs represents approximately 2% and is expected to have little measurable impact on treatment time. The additional organic load from the FIWs represents approximately 10% of the base sludge loading (on a COD basis). The organic loading rates within this experiment are moderate as compared to the typical loadings of mesophilic mixed liquor digesters (Mata-Alvarez et al., 2014).

Table 13: Summary of Operating Parameters during Experiment 1

Parameter	**Start up**	**Baseline**	**Co-digestion Period**
Operating Temperature (°C)	38	38	38
Biogas Recirculation rate (m^3/m^3/h)	0.2	0.2	0.2
Mixing Strategy	Cycle: 30 mins on 30 mins off	Cycle: 30 mins on 30 mins off	Cycle: 30 mins on 30 mins off
AD operating Volume (L)	2,400	2,400	2,400
Sludge RT (d)	45	20	20
Sludge Load (L/d)	51.4	120	120
Sludge OLR (base) (kgCOD/m^3/d)	1.32	2.5	2.5
Co-substrate Load (L/d)	0	0	1
GTW	0	0	2.5
Nominal Co-substrate OLR (kg/m^3/d)	0	0	0.22
Total OLR (kg/m^3/d)	1.32	2.5	2.72
Adjusted SRT (d)	45	20	19.4
Sludge feeds per day (d^{-1})	0.43	4	4
Sludge vol. per feed (L)	120	30	30
TW feeds per day (d^{-1})	0	0	1
TW vol. per feed (L)	0	0	2.5

Start-up period – SRT of 45 days. Semi-continuous feed with PS and TWAS at a 50%:50% volume basis. Reactor feed events occurred three times per week where 120L was fed during a 48hr cycle. Organic loading rate (OLR) was 1.32 kg/m3/d.

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Baseline period – SRT reduced from 45 days to 20 days. Continuous operation fed with sludge only (PS and TWAS at a 50%:50% volume basis). Reactor feed events occurred four times per day where 30L was fed during a 6hr cycle. OLR was 2.45 kg/m3/d.

Experimental period (Exp.1.1) – SRT of 20 days. Continuous operation fed with PS and TWAS at a 50%:50% volume basis, plus additional 10% FOG. Reactor feed events occurred four times per day where 30 L of sludge mixture (PS+TWAS) was fed during the first three 6hr cycles, and 33 L (PS+TWA+FOG) was fed during the fourth 6hr cycle. OLR was 2.70 kg/m3/d.

3.2.1.3 Process Performance

Biogas production from the pilot digester at different operational periods is shown in Figure 11 (middle graph). The red dotted lines indicate the theoretical biogas production from the feed material at the digester SRT conditions, based on model estimation from laboratory batch tests results (presented previously in Table 12).

During the Start-up period (I), the observed biogas production was approximately 270 L/m^3.d, which was generally consistent with the biogas production predicted from batch testing. During the Baseline period (II) to the Experimental period (III), the observed biogas production gradually increased from 267 L/m^3.d and stabilised at 764 ± 194 L/m^3.d. During the first 7-10 days of the baseline period the biogas production from the pilot plant was below model predictions and may indicate a period of acclimation to the step change in organic load. By the end of the baseline period the pilot was outperforming model predictions in both biogas production and VS destruction. Pilot plant operation experienced a major external disruption from Day 146 to Day 160, biogas production was again slow to respond after this period of disruption demonstrating that process changes represent a transient risk.

During periods of stable operation, comparisons of the pilot plant performance and batch tests show that over 88% of the degradable material was converted to methane in the pilot plant. The biogas composition was typically 60-63% CH_4 and 37-40% CO_2.

Volatile solid destruction levels in the pilot plant were variable with an average VS destruction reached and stabilised above 50% (Figure 11 – bottom), this exceeds the results from laboratory tests where VS destruction of approximately 38-42% is expected in a continuous reactor with an SRT of 20 days.

Overall, Experiment 1 was largely successful in validating the laboratory BMP results as a predictor of steady state behaviour. However, this experiment also demonstrates an acclimation period between process changes. While the process will adapt to disruptions or shifts in operating conditions, there is a risk of exceeding process limits during the acclimation period.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

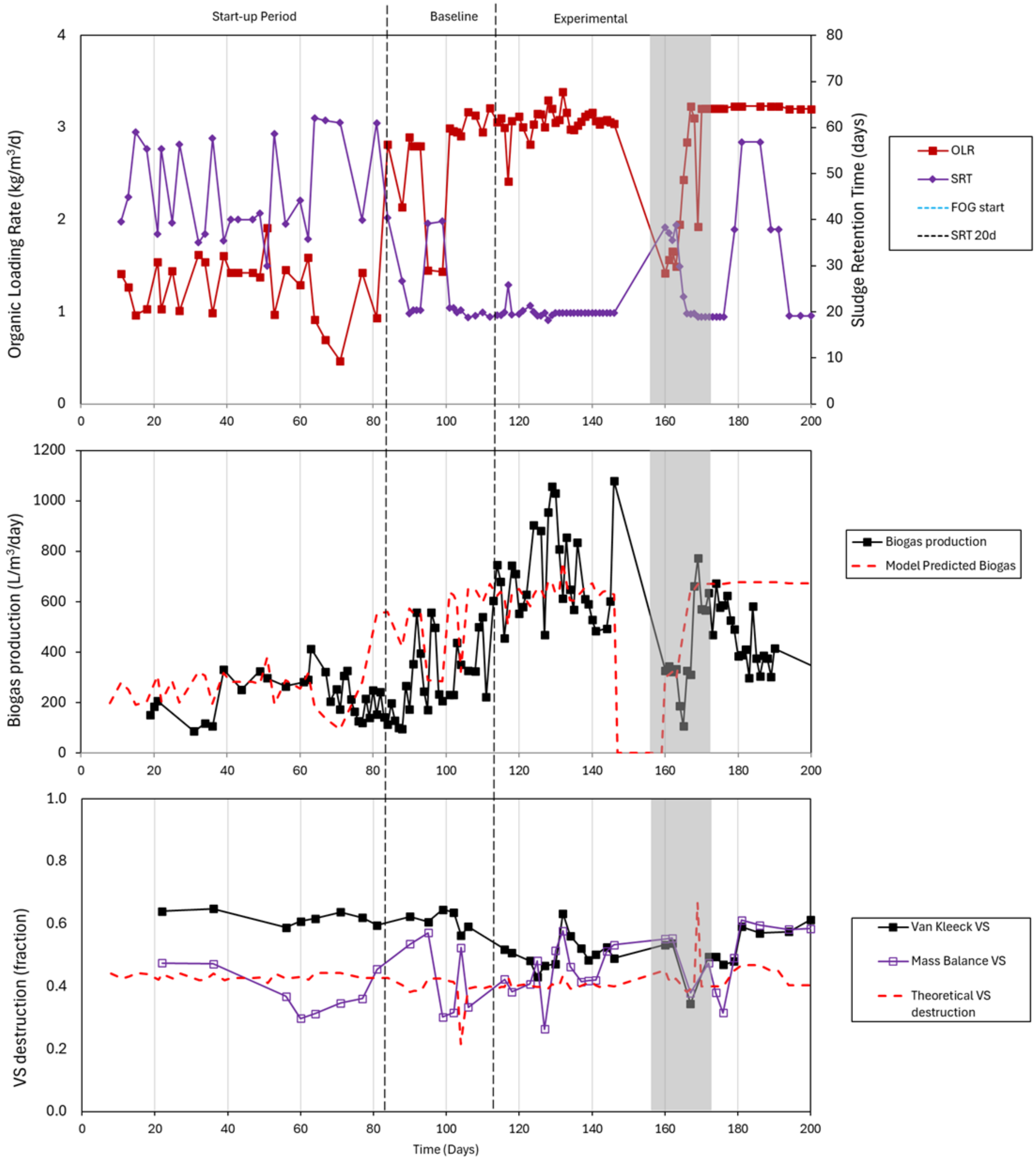


Figure 11 Anaerobic Digestion Pilot Plant data during Experiment 1. Top: SRT and OLR. Middle: Daily biogas production profile. Bottom: VS destruction. The shaded areas indicate operational interruptions (i.e. TC-Alfred, equipment repair).

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

3.2.2 *Experiment 2 – Assessing Co-digestion at Future Commercial Organic Loads*

Experiment 2 was designed to increase co-substrate loading rates to represent future commercial opportunities and assess the impact on process performance.

3.2.2.1 Pilot Operating and Loading Strategy

Table 14 is a summary of the operating parameters and co-substrate loading to each pilot during Experiment 2. Nominal sludge loading during Experiment 2 is based on 2.5 kgCOD/m^3.d. The co-substrate using in Experiment 2 was GTW at nominal organic addition rates of 10% (0.25 kgCOD/m^3.d), 20% (0.5 kgCOD/m^3.d) and 50% (1.25 kgCOD/m^3.d) of the base sludge load. Loading rates were selected to explore GTW loading from 2023/2024 (10%), targeted GTW loading (20%) and a potential future load (50%).

Table 14: Summary of Operating Parameters during Experiment 2

Parameter	Co-digestion Period 10% Loading	Co-digestion Period 20% Loading	Co-digestion Period 50% Loading
Operating Temperature (°C)	38	38	38
Biogas Recirculation rate (m^3/m^3/h)	0.2	0.2	0.2
Mixing Strategy	Cycle: 30 mins on 30 mins off	Cycle: 30 mins on 30 mins off	Cycle: 30 mins on 30 mins off
AD operating Volume (L)	2,400	2,400	2,400
Sludge RT (d)	20	20	20
Sludge Load (L/d)	120	120	120
Sludge OLR (base) (kgCOD/m^3/d)	2.5	2.5	2.5
Co-substrate Load (L/d)	4	4	4
GTW	2.5	5	10
Co-substrate OLR (kg/m^3/d)	0.22	0.45	0.9
Total OLR (kg/m^3/d)	2.72	3.0	3.4
Adjusted SRT (d)	19.4	19.2	18.5
Sludge feeds per day (d^{-1})	4	4	4
Sludge vol. per feed (L)	30	30	30
TW feeds per day (d^{-1})	1	1	1
TW vol. per feed (L)	2.5	5	10

3.2.2.2 Process Performance

Biogas production from the pilot digester during each operational period of Experiment 2 is shown in Figure 12 (middle graph). The red dotted lines indicate the theoretical biogas production from the feed material at the digester SRT conditions, based on model estimation from laboratory batch tests results (presented previously in Table 12).

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

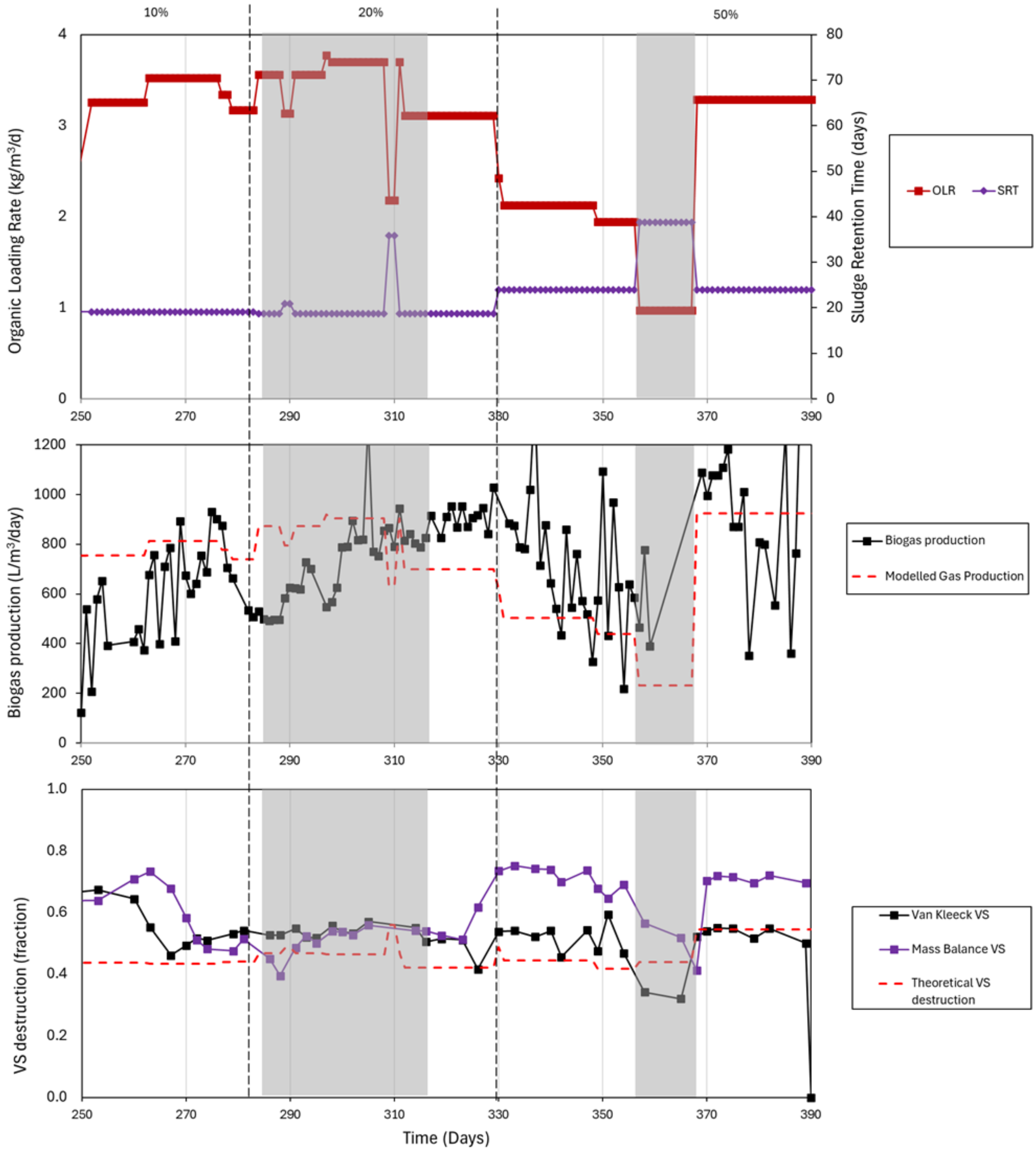


Figure 12 Anaerobic Digestion Pilot Plant data during Experiment 2. Top: SRT and OLR. Middle: Daily biogas production profile. Bottom: VS destruction. The shaded areas indicate operational interruptions (i.e. equipment repair).

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

During the 10% loading period, the organic loading rate ranged from 3.1 to 3.4 kgCOD/m^3/d, which was higher than the planned loading rate of 2.72 kgCOD/m^3/d. Biogas production during this period was initially much lower than predictions from batch tests, but recovered to expected levels by the end of the test period. Equipment issues impacted results during the first part of the 20% loading period, these issues were resolved around Day 320 during the period that followed the OLR was maintained at approximately 3 kgCOD/m^3/d with biogas production of 800 - 1000 L/m^3.d recorded, this was significantly higher than the predicted biogas production of 700 L/m^3.d. The 50% loading period commenced on Day 330, the GTW received from Day 330 to Day 360 was significantly lower in concentration compared to previous samples and this resulted in an OLR that was much lower than expected. GTW imports from Day 370 were at more typical concentrations and the OLR was successfully increased to target levels of approximately 3.4 kgCOD/m^3/d, biogas production during this period was initially over 1000 L/m^3/d, but was generally quite variable. Variable biogas production may be an indication of biological stress and poor process stability.

Volatile solid destruction levels in the pilot plant stabilised around 50% (Figure 12 – bottom), this exceeds the results from laboratory tests where VS destruction of approximately 40-52% is expected in a continuous reactor with an SRT of 20 days. There was some disagreement when comparing the VS destruction results obtained from the mass balance and the Van Kleeck method, which may be explained by variations in the composition of primary sludge used as feed. The strength of primary sludge varied from 4% TS to 7% TS, although there were very minor variations in the VS/TS ratio which implies that differences in PS were the result of variable thickening performance rather than changes in the type of organic material. Changes in sludge concentration but not organic composition will impact the mass balance VS destruction to a much higher degree than the Van Kleeck VS destruction and as a result the Van Kleeck results are likely more useful predictors of process performance.

Overall, Experiment 2 demonstrates that the pilot plant performance exceeded BMP predictions during steady operation. However, this experiment also demonstrates that feed characteristics are highly variable with clear impacts on plant operation. The effluent solids concentrations were more stable and more consistent than biogas production data and the mass balance VS destruction results, which suggests that solids loading to downstream dewatering units remain relatively consistent and predictable.

3.2.3 Biogas Production Dynamics and Response to Co-substrate Dosing

Biogas production from the pilot plant and the corresponding tank headspace pressure (PHS) were continuously monitored throughout the experimental period. This section presents representative 24-hour gas production profiles for pilot operation receiving GTW at 10% of organic load (Figure 13), 20% of organic load (Figure 14) and 50% of organic load (Figure 15). Each 24 hour period contained three feeds consisting of sludge mixture (TWAS + PS), and one feed containing sludge mixture and an additional spike of GTW. This loading strategy simulates the impact of a full GTW tank load arriving onsite and being introduced into the anaerobic digester.

In general, each feed event (indicated by grey arrows) triggered a rapid rise in both biogas production rate and headspace pressure, with peak gas production typically occurring approximately one-hour post-feeding. During the 10% loading period the biogas peaks were approximately 120 L/m^3/hr from the sludge only feeds, but were 25% higher after the GTW-spiked feed (~150 L/m^3/hr). The GTW was expected to increase daily biogas production by an average of 10-15%, however the biogas dynamics study demonstrates that degradation is not uniform and the microbial community had redundant metabolic capacity that responded to the spiked organic load through more rapid biogas production. During the 20% loading period the biogas peaks were higher at approximately 200 L/m^3/hr from the sludge only feeds, and increased to 275 L/m^3/hr after the GTW spiked feed (35% increase), similar peaks of 275 L/m^3/hr were recorded during the 50% loading period, which seems to represent the limit of the system biology.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Notably, biogas production was highly dynamic and sensitive to the digester's intermittent gas mixing strategy, which operates on a 30-min ON / 30-min OFF cycle. Gas release rates were consistently higher during mixing-ON periods, attributed to improved mass transfer and bubble detachment facilitated by active mixing. The level of impact was variable and seemed to be greater in the periods after the pilot was fed, with biogas production rates varying by up to 100% between mixing-ON and mixing-OFF phases. The impact of mixing on gas production dynamics and biogas release rates needs to be investigated further to develop practical knowledge to guide full-scale digester gas management strategies, such as implementing real-time feed control based on pressure feedback or optimising mixing regimes to manage pressure surges following high-load GTW additions.

Overall, biogas production rates in the pilot system ranged from approximately 50 to 275 L/m³/hr over a typical 24-hour cycle, influenced by both the feedstock composition and the applied mixing strategy. The findings indicate that mixing plays a dominant role in modulating gas production, primarily through mass transfer enhancement, with implications for biogas capture and utilisation infrastructure that warrant further investigation. From these results it is clear that monitoring changes in average daily biogas production are not sufficient to understand the impacts to co-substrate dosing and biogas dynamics must be considered to ensure gas handling limits are not exceeded.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

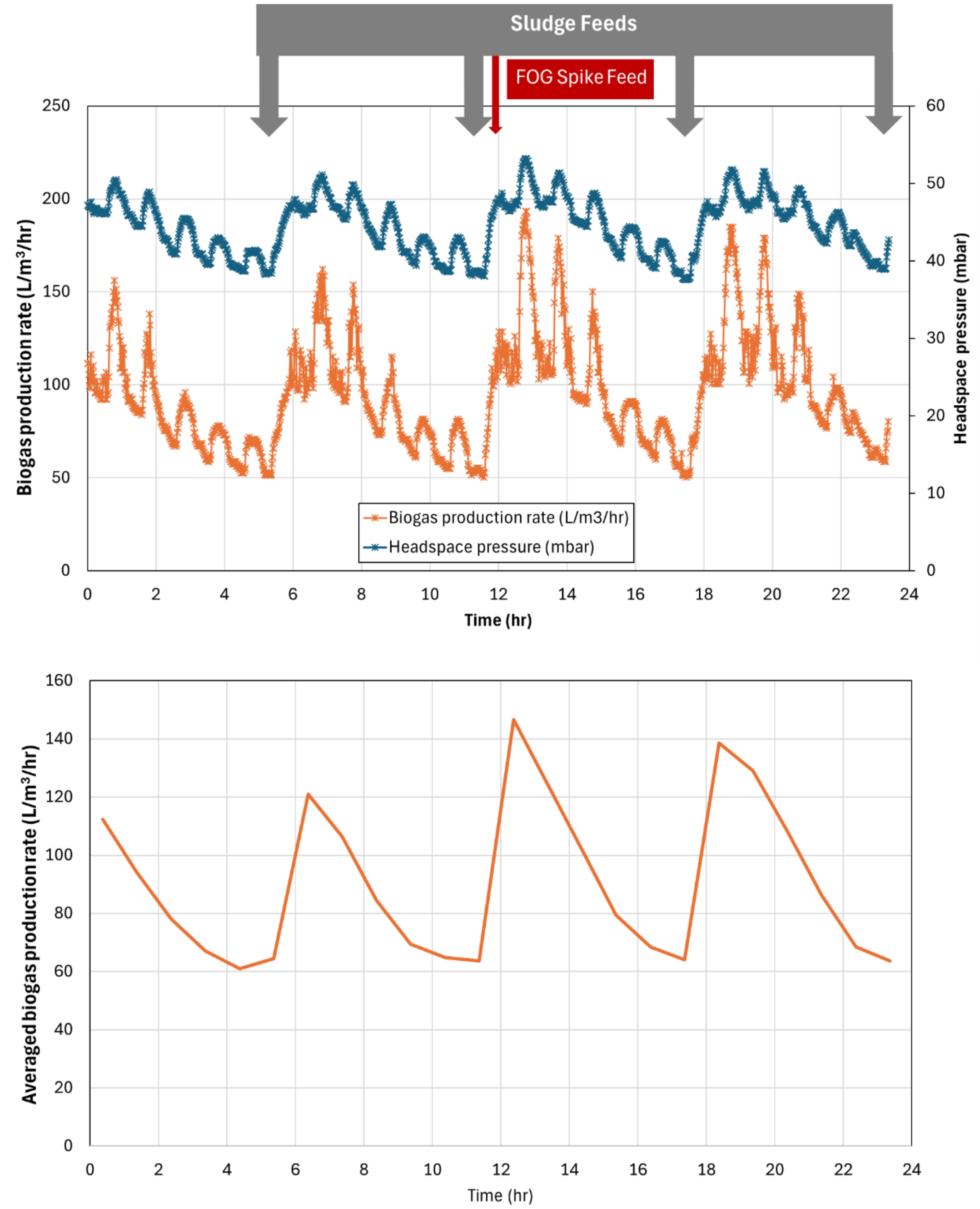


Figure 13 biogas production profile during 24 hr period that contained four sludge feed events, including one GTW spike at 10% of daily organic load. Top: Biogas production rate and headspace pressure in response to gas mixing ON-30min/OFF-30min cycles. Bottom: Average biogas production rate over 6-hour windows following each feed event.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

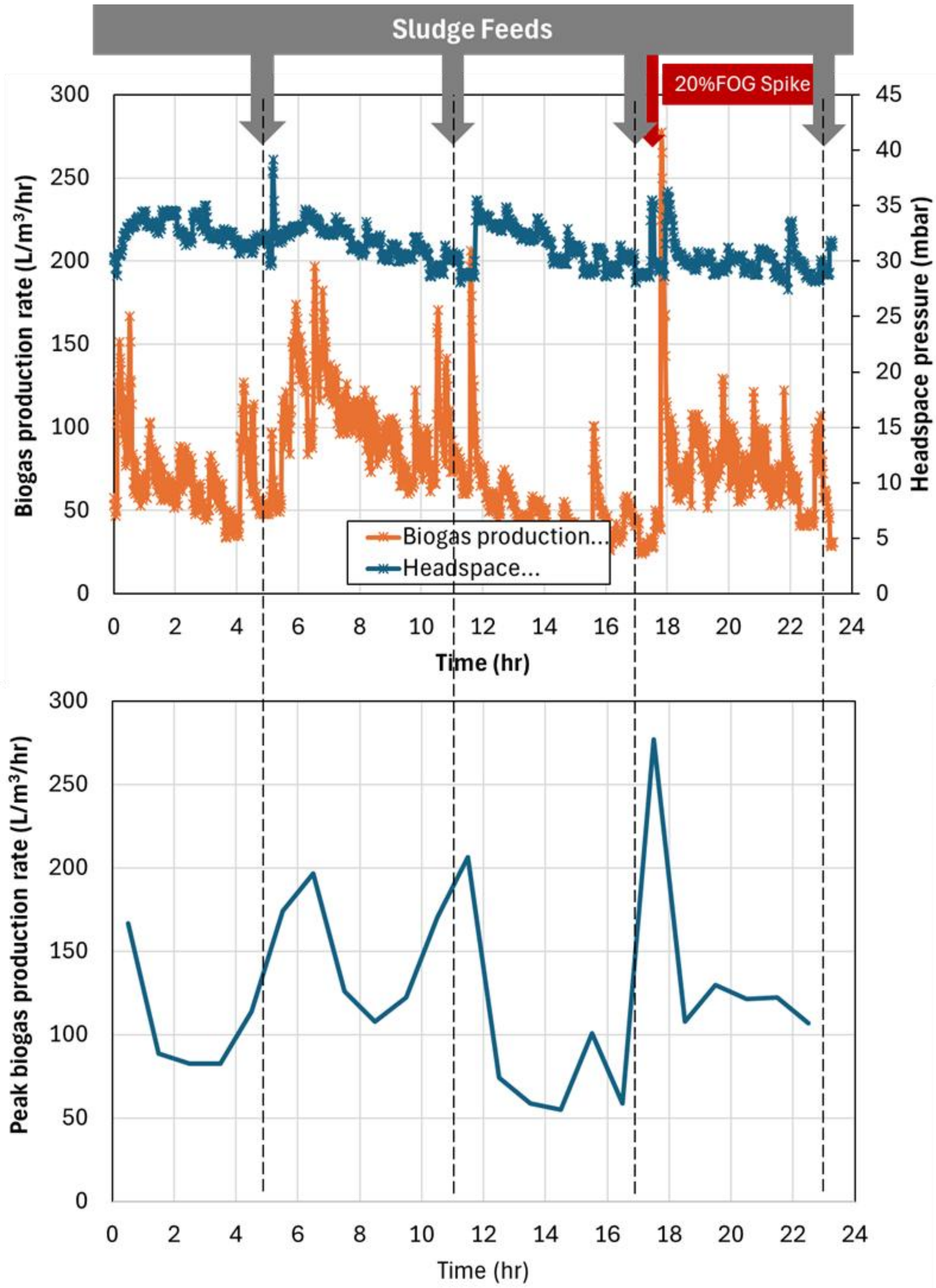


Figure 14 biogas production profile during 24 hr period that contained four sludge feed events, including one GTW spike at 20% of daily organic load. Top: Biogas production rate and headspace pressure in response to gas mixing ON-30min/OFF-30min cycles. Bottom: Average biogas production rate over 6-hour windows following each feed event.

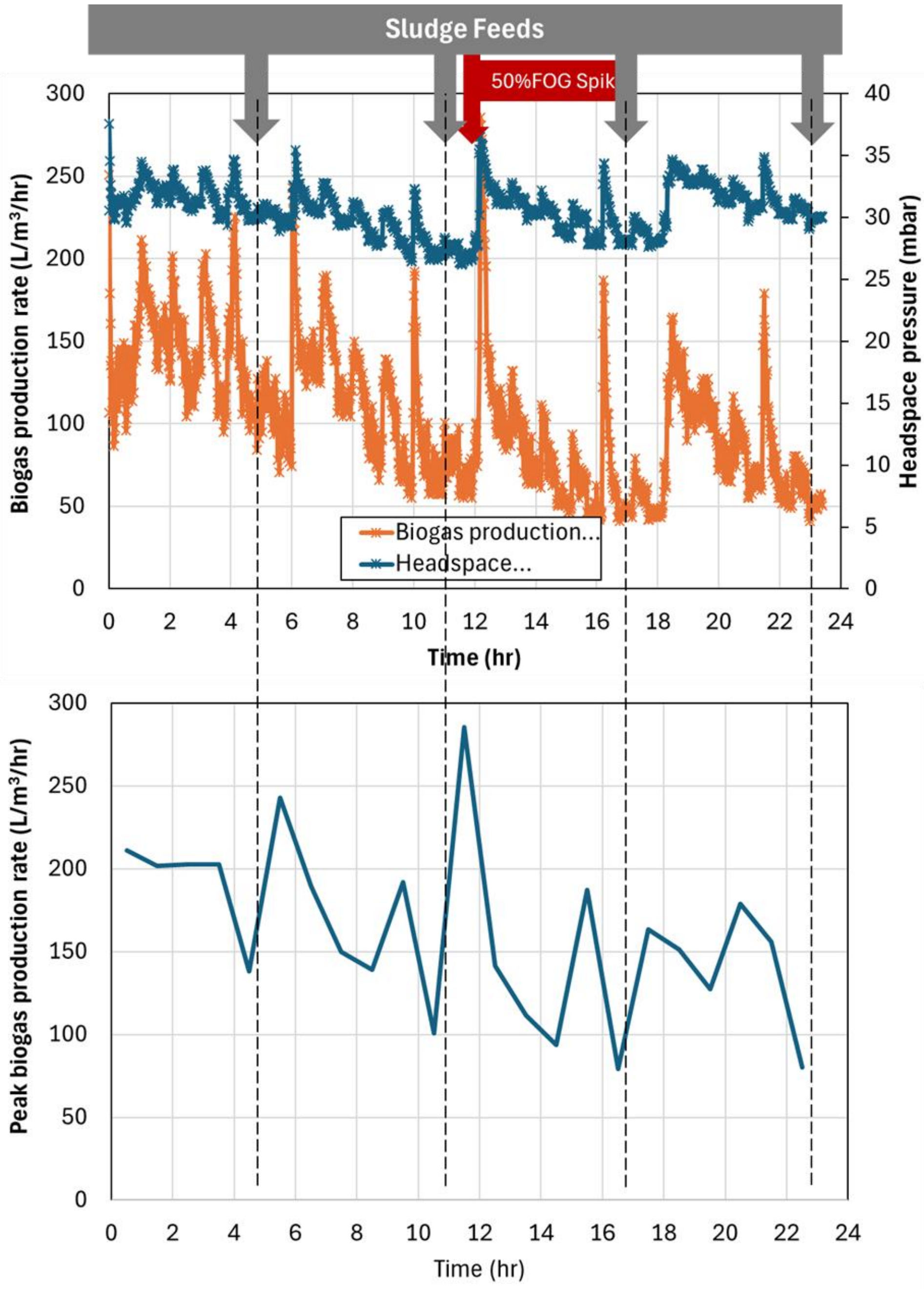


Figure 15 biogas production profile during 24 hr period that contained four sludge feed events, including one GTW spike at 50% of daily organic load. Top: Biogas production rate and headspace pressure in response to gas mixing ON-30min/OFF-30min cycles. Bottom: Average biogas production rate over 6-hour windows following each feed event.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

3.2.4 Impact of Co-digestion on Biosolids Quality

3.2.4.1 Additional Volatile Solids Reduction

Additional volatile solids reduction (AVSR) was measured to evaluate biosolid stabilisation against criteria in End-of-Waste Code (ENEW07359617) and against the performance on the full-scale digesters at LP STP. AVSR was measured for effluent streams from the pilot scale digester and was done prior to any dewatering operations.

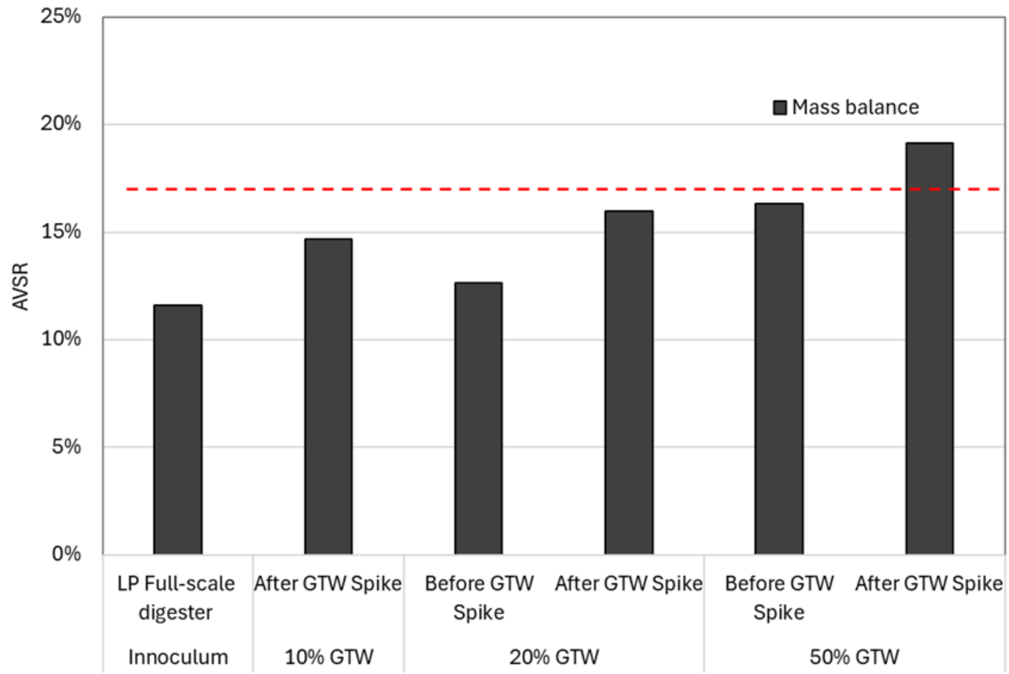
Sludge samples were collected directly from the pilot-scale digester, and a full-scale digester. Each sample was analysed for TS and VS at the start of the test (t=0), and at the end of the test (t=40 d). Two VS destruction formulas were applied (Section 2.1.3): the Van Kleeck calculation and the mass-balance calculation with the results summarised in Figure 16. This dual-method approach enables a more nuanced understanding of digester performance and highlights potential influences from operational and sampling variables.

Figure 16 shows a noticeable discrepancy in AVSR values for the full-scale system, with only 4.4% calculated by the Van Kleeck method compared to 11.6% by mass balance. This divergence could be attributed to chemical dosing within the wastewater treatment plant, which may have resulted in precipitation of fixed solids during the AVSR test, skewing the VS:TS ratio and consequently underestimating actual volatile solids destruction in the Van Kleeck calculation. Regardless, full-scale digestate AVSRs passed the ENEW07359617 regulatory threshold as “no greater than 17%”.

The AVSR results for the pilot-scale show:

i) The AVSR was higher in samples collected directly after a feed event and improved in samples collected several hours after a feed event - Feed events add fresh untreated material to the digester which reduces the overall stability of the digester contents on a short term basis. The pilot plant operates with a simultaneous feeding and wasting strategy, which is common practice for commercial anaerobic digesters. Simultaneous feeding/wasting increases the risk of short-circuiting during feed events where feed material bleeds through the system without correct treatment. Short-circuiting during feed events can result in digestate that fails EoW stability tests for a period of time, further testing is required to assess mixing dynamics in the reactor, the extent of short-circuiting and the period of EoW non-compliance that may occur during large feed events.

ii) There was a general trend for the stability of material to decrease as the GTW loading increased and there is a significant risk that the dewatered sludge will not meet EoW stability requirements for land application, however the conclusions were different depending on whether the Mass Balance approach or the Van Kleeck approach was used. Additional data is needed to determine the process limits in relation to AVSR and EoW compliance.



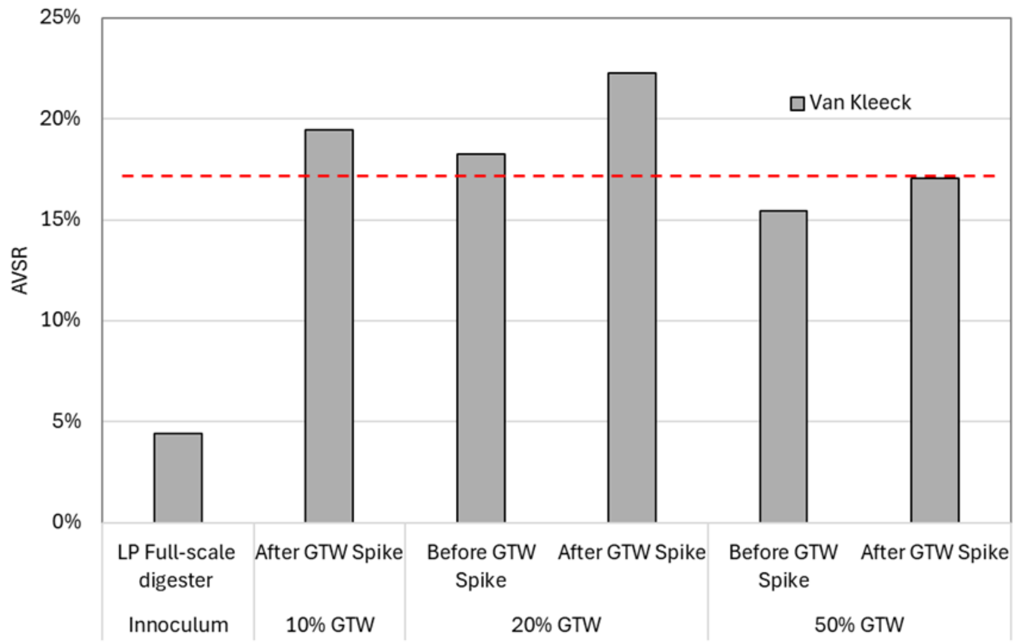


Figure 16 Additional volatile solids reduction (AVSR) tested on the full-scale AD digester and Pilot digester. The dashed red line indicates the maximum AVSR allowed under the Biosolids EoW compliance.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

3.2.4.2 Regulated Contaminant Levels – Trace Metals

The concentrations of heavy metals were measured to evaluate the composition of the pilot plant biosolids against criteria in End-of-Waste Code (ENEW07359617, shown in Table 15) and against the performance on the full-scale digesters at LP STP. Heavy metals were measured for effluent streams from the pilot scale digester and the post-AD tank and was done prior to any dewatering operations with results shown in Table 16.

The biosolids at the pilot plant site were assessed as Class C biosolid based on the copper and zinc concentrations of the baseline material. The Food Industry Wastes examined in this project contained significantly lower heavy metal concentrations when compared to mixed sewage sludge, which had a dilution effect and resulted in lower contaminant levels in the resulting digestate. At GTW loading of 50% the zinc concentrations of the digestate were diluted to below 700 mg/kg meeting the requirements for Class B biosolid, the copper concentrations were also reduced and may also meet the requirements for Class B biosolid, however these findings are based on a single sample point and additional data is required to understand the long term implications. Importantly, the metal contaminant levels in the FIWs were consistently lower than the baseline sludge and this means there will be no negative impacts on biosolids class.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Table 15: Class limits for selected heavy metal contaminants as presented in ENEW07359617

mg/kg dry weight	Arsenic	Cadmium	Chromium (total)	Copper	Lead	Nickel	Selenium	Zinc
EoW Class A	20	3	100	150	150	60	5	300
EoW Class B	20	5	250	375	150	125	8	700
EoW Class C	20	20	500	2000	420	270	50	2500

Table 16: Selected heavy metal contaminants in pilot plant samples at each GTW loading rate (colour coded to EoW class).

		Arsenic	Cadmium	Chromium (total)	Copper	Lead	Nickel	Selenium	Zinc
Co-substrates	*GTW*	<0.01	<0.01	4 ± 2.6	98 ± 23	3.8 ± 6.5	2 ± 1	<0.01	86 ± 24
	DW	<0.01	<0.01	<0.01	18 ± 48	<0.01	1 ± 1	<0.01	48 ± 29
Startup	AD	5.6 ± 5	<0.01	45.3 ± 2.2	410 ± 40	31.7 ± 4.5	30 ± 2	<0.01	801 ± 68
	Post-AD	7.8 ± 6.9	<0.01	48.2 ± 2.3	459 ± 5	36.3 ± 3.5	32 ± 1	<0.01	909 ± 25
Baseline	AD	3.7 ± 7.1	0.3 ± 0.6	43.3 ± 10.7	413 ± 99	28.7 ± 3.8	30 ± 7	0.9 ± 1.8	791 ± 152
	Post-AD	9.3 ± 6.8	0.6 ± 0.7	44.8 ± 6.6	401 ± 82	35.3 ± 8.3	33 ± 9	<0.01	859 ± 182
10%FOG	AD	2.1 ± 4.2	0.1 ± 0.3	50.7 ± 7.9	420 ± 67	26.9 ± 9.4	29 ± 4	1.7 ± 4.7	835 ± 107
	Post-AD	4.7 ± 7.4	<0.01	50.3 ± 14.8	415 ± 88	25.8 ± 11.6	27 ± 6	<0.01	844 ± 188
20%FOG	AD	<0.01	<0.01	46.1 ± 16.8	444 ± 79	<0.01	0 ± 24	<0.01	713 ± 182
	Post-AD	<0.01	<0.01	50.8 ± 0	472 ± 15	<0.01	14 ± 20	<0.01	775 ± 4
50%FOG	AD	<0.01	<0.01	34.6 ± 0	333 ± 0	<0.01	<0.01	<0.01	535 ± 0
	Post-AD	<0.01	<0.01	44.2 ± 0	420 ± 0	<0.01	<0.01	<0.01	677 ± 0

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

3.2.4.3 Dewaterability

This section presents results of dewaterability testing on digestate samples collected from the pilot plant. The results in Figure 17 show there was no significant impact on dewaterability at low GTW addition rates, however as GTW dosing increased there may be a decline in dewatering performance. Reductions in dewaterability and the corresponding increase in water retained within the biosolid can significantly increase the total mass of biosolids that must be managed and transported and can have significant implications on biosolids management costs. A change in dewaterability from 20% to 15% (as implied by Figure 17), could increase the total mas of biosolids after centrifuge dewatering by 33% and could have substantial cost implications. Currently dewaterability has been assessed on only a small number of samples using a centrifuge-based method, further testing is required to examine the impact of co-digestion on biosolids dewatering and determine if reductions in centrifuge dewaterability will be maintained through subsequent drying units.

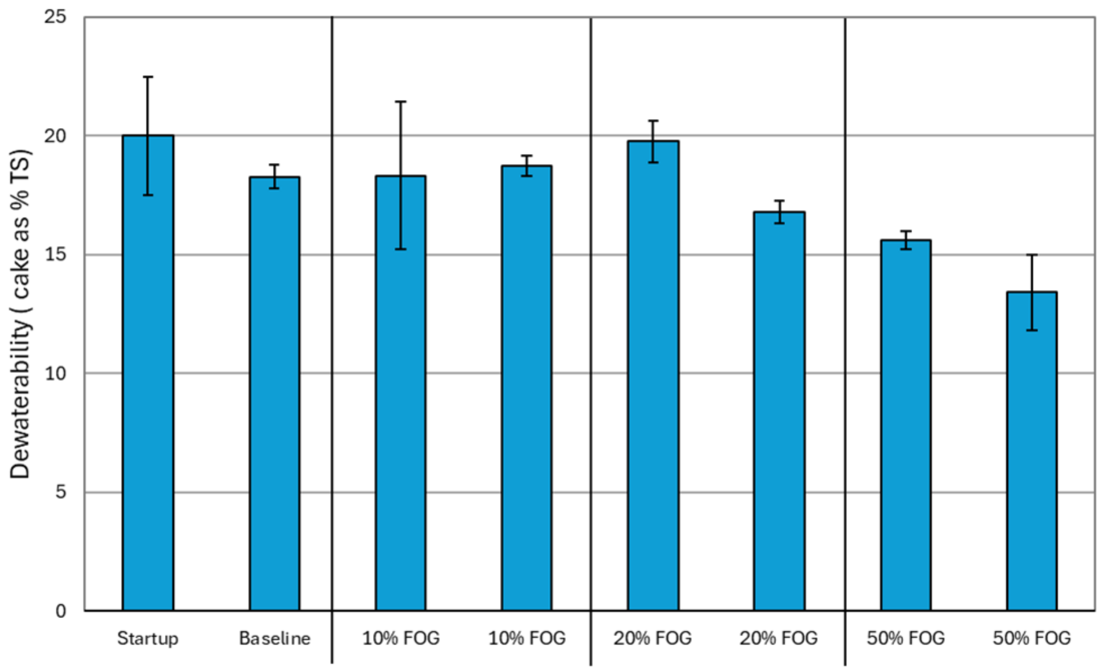


Figure 17 Results from Laboratory Scale Dewaterability Analysis of Pilot Plant Digestate Samples.

3.3 Co-digestion Scenario 1: Import of Solid Food Waste to a Municipal WWTP treating Sewage Sludge

3.3.1 Scenario Description and Experimental Data

Co-digestion Scenario 1 examines the import of Solid Food Waste to a Municipal WWTP. SFW is not currently being added to the commercial digesters at the host site due to challenges in materials handling, however the current commercial target is to import SFW corresponding to 34% of the sludge organic load currently being treated. The volume of SFW available locally is significantly larger than the target, which implies there may be future commercial opportunities to process much higher volumes. During this

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

experiment, SFW was examined at 25, 50, 75 and 100% of the sludge COD load. Where SFW is distributed among the 5 operating digesters this range would exceed commercial targets, but was selected to examine a scenario where SFW imports were added to only 1 or 2 of the operating digesters (potentially reducing infrastructure upgrades to handle the high solids material). Kinetic parameters from the SFW co-digestion experiment are summarized in Table 17 with methane production curves included in Appendix A. Addition of SFW resulted in a significant increase in methane produced from the batch tests, however there was only minor change in methane production on a normalized solids basis (m^3/kg VS added). The SFW used in these experiments was more biodegradable than the sewage sludge base (demonstrated by the higher degradable fraction), but was less energy dense than sewage sludge (demonstrated via a lower COD/VS ratio) as a result the overall degradable fraction of the mix was impacted to a larger degree than the normalized methane production (m^3/kg VS added). For example, normalized methane production improved from 299 m^3/kg VS added during the base sludge to 338 m^3/kg VS added during SFW co-digestion experiments (approx. 10% increase) while degradable fraction improved from 52% in the base sludge tests to 65% in the SFW co-digestion tests (approx. 25% improvement).

The SFW used in this experiment degraded less rapidly than samples analyzed in Section 3.1.3 (0.29 day^{-1} compared to 0.44 day^{-1}) No lag period or inhibition was observed in the tests at any loading rate examined and there was no clear trend in apparent first order hydrolysis rate and therefore no clear impact on degradation speed. However, increased volume load will have a corresponding impact on treatment times that may reduce waste conversion within a continuous process, this impact is explored using the CSTR model and presented in Table 18. It is also important to note the SFW used in this experiment degraded less rapidly than samples analyzed in Section 3.1.3 (0.29 day^{-1} compared to 0.44 day^{-1}) and this may impact conversion within the model digester.

Table 17: Kinetic parameters estimated during batch co-digestion of SFW and sewage sludge (with 95% CI).

Substrate	Apparent Hydrolysis Rate k_{hyd} (d^{-1})	Methane Potential *B0* (m^3 CH4/kg VS)	Degradable Fraction *fd* (Estimated by modelled co-digestion parameters)	Degradable Fraction *fd* (Estimated using mono-digestion parameters)
Mono-digestion				
PS + TWAS	0.26 ± 0.04	299 ± 14	0.52 ± 0.04	
SFW	0.29 ± 0.06	385 ± 16	0.79 ± 0.04	
Co-digestion				
+25% SFW	0.26 ± 0.05	320 ± 16	0.61 ± 0.03	0.58 ± 0.07
+50% SFW	0.29 ± 0.05	338 ± 16	0.65 ± 0.04	0.61 ± 0.07
+75% SFW	0.28 ± 0.04	338 ± 14	0.65 ± 0.04	0.64 ± 0.08
+100% SFW	0.26 ± 0.03	337 ± 15	0.66 ± 0.03	0.65 ± 0.08

3.3.2 *Model-based Assessment of Process Performance and Process Limits*

This section summarises process performance predictions during co-digestion of SFW at a municipal treatment plant simulated using the CSTR model. Table shows that SFW loading rate had limited impact on process kinetics, therefore Table was generated using kinetic parameters from mono-digestion controls (Table) and assumes the degradation of each waste stream is independent and not impacted by loading rate.

Model simulations show that SFW could be imported to the host site safely at levels corresponding to a 20% increase in organic load. This addition rate would increase methane production by 30% (from 1910 m^3/d to 2493 m^3/d). The increase in centrate nitrogen was similar at 25% (from 237 kg/d to 296 kg/d) and is consistent with the similar COD/N ratios of SFW and sewage sludge. The increase in biosolids production was significantly lower at <10% (33.9 tons/day compared to 31 tons/day), and importantly the model predicts that the biosolids would still meet the ASVR requirements in EoW codes under this operation.

The import target for SFW at the host site corresponds to an increase in organic load of 34%. Batch tests were able to treat SFW at significantly higher addition rates (up to 100%) with no clear impact on process kinetics, however the increase in volume load would reduce the treatment time (SRT) in the digesters by around 10% (from 22.6 days to 20.5 days). The CSTR model shows that this decrease is treatment time is significant enough to impact EoW compliance.

Table 18: CSTR model examining the impact of SFW co-digestion at a Municipal WWTP (modelling using k_{hyd} and f_d parameters fitted to mono-digestion experiments in Table 17)

Parameters	Baseline	10% SFW	20% SFW	34% SFW	50% SFW	100% SFW
Sludge Load (m^3/d)	Commercial in Confidence					
SFW Load (m^3/d)	Commercial in Confidence					
SRT (d)	22.6	22.0	21.4	20.5	19.9	17.7
OLR-COD (kg/m^3.d)	2.8	3.0	3.3	3.7	4.0	5.2
OLR-VS (kg/m^3.d)	1.7	1.9	2.1	2.4	2.6	3.5
CH_4 Production (m^3/d)	1910	2203	2493	3013	3352	4743
Biosolid Production (ton/d)	31	32.3	33.9	36.9	38.9	47.4
Centrate N (kg/d)	237	267	296	345	375	493
Centrate P (kg/d)	77	85	93	105	113	140
Residual Degradability (% of VS)	13.4	14.6	15.8	17.8	19.0	23.4
AVSR	12.7	13.9	15.0	17.1	18.2	22.2
EoW Code	Pass	Pass	Pass	Risk	Fail	Fail

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

3.4 Co-digestion Scenario 2: Import of Grease Trap Waste to a Municipal WWTP treating Sewage Sludge

3.4.1 Scenario Development and Experimental Data

Co-digestion Scenario 1 focused on the import of grease trap waste to a municipal wastewater treatment plant. On an organic load basis, GTW was the largest FIW stream imported to the host facility in 2023/24 and remains a target waste import due to very high organic strength of this waste and the limited nutrient content. Target import levels for GTW correspond to an ~80% increase in organic load if added to a single digester or 16% if distributed across the 5 operating digesters. To explore this range, and potential future commercial opportunities, GTW was tested at 10, 20, 50, 100, 150, and 200% of the sludge COD load. Kinetic parameters from the GTW co-digestion experiment are summarized in Table 19 with methane production curves included in Appendix B, the results show a progressive increase in methane production as GTW load increases. While an increase in methane production is expected from the increased COD load, the normalized methane production (m^3/kg VS) and the degradable fractions also increased and this was due to the high energy potential and the relatively high biodegradability of the GTW COD.

A lag period was evident in tests with GTW loading above 50%, indicating an inhibition risk above these levels. In tests where GTW was added at 50% of organic load, the GTW dose corresponded to 2.2% of the test volume at start up. In tests where GTW was added at 100% of organic load, the GTW dose corresponded to 4.2% volume. The combination of these results suggests that inhibition onset occurs when GTW is 2-4% of the reactor volume; corresponding to 48 -96 L of GTW added to the pilot plant or 100-200 m^3 of GTW added to a single commercial digester at the host site. The lag time increased as GTW dosing increased above 100%, however the inhibition that was observed was temporary and the final gas production was consistent with model predictions.

Process kinetics appeared to be enhanced at lower GTW addition rates (0.21-0.22 day^{-1} for mixtures of 10-20% GTW compared to <0.2 day^{-1} for the mono-digestion, this may represent a minor synergy where GTW breaks down quickly at low concentrations. As GTW dose increase, there was a trend for apparent hydrolysis rate (k_{hyd}) to decrease, however the effects were relatively minor at dose rates of up to 150%. Regardless, the combined impacts of increased volume load, decreased treatment times and decreased process rates are explored using the CSTR model and presented in Table 21.

Table 19: Kinetic parameters estimated during batch co-digestion of GTW (with 95% CI).

Substrate	Delay Time *td* (d)	Apparent Hydrolysis Rate k_{hyd} (d^{-1})	Methane Potential *B0* (m^3 CH_4/kg VS)	Degradable Fraction *fd* (Modelled from co-digestion data)	Degradable Fraction *fd* (Estimated using mono-digestion parameters)
Mono-digestion					
PS		0.17 ± 0.04	326 ± 21	0.52 ± 0.04	
TWAS		0.11 ± 0.04	194 ± 22	0.48 ± 0.04	
GTW	12.3 ± 0.4	0.18 ± 0.03	834 ± 34	0.83 ± 0.04	
PS + TWAS		0.19 ± 0.05	230 ± 22	0.56 ± 0.04	
Co-digestion					
+10% GTW		0.21 ± 0.05	255 ± 22	0.51 ± 0.04	0.53 ± 0.06
+20% GTW		0.22 ± 0.05	299 ± 22	0.54 ± 0.04	0.55 ± 0.07
+50% GTW		0.19 ± 0.06	436 ± 26	0.54 ± 0.04	0.61 ± 0.07
+100% GTW	2.3 ± 0.6	0.17 ± 0.04	554 ± 24	0.70 ± 0.05	0.66 ± 0.08
+150% GTW	11.4 ± 0.6	0.18 ± 0.04	677 ± 28	0.75 ± 0.04	0.70 ± 0.08
+200% GTW	12.3 ± 0.6	0.12 ± 0.02	722 ± 32	0.69 ± 0.05	0.72 ± 0.09

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

3.4.2 Model-based Assessment of Process Performance and Process Limits

This section summarises process performance predictions during co-digestion of GTW at a municipal treatment plant simulated using the CSTR model. Table 20 was generated using kinetic parameters from mono-digestion experiments (Table 19) and assumes the degradation of each waste stream is independent and not impacted by loading rate, this simulation is likely representative of steady state operation after an acclimation period. Results shows that GTW could be imported to the host site safely at levels corresponding to a 20% increase in organic load. This addition rate would increase methane production by 35% (from 1910 m^3/d to 2568 m^3/d). At this GTW addition rate, biosolids production would increase by 3% (32 tons/day compared to 31 tons/day) and centrate nitrogen would increase by 7% (from 237 kg/d to 255 kg/d). These results demonstrate that GTW has a much more significant impact on methane production and a lower impact on cost factors (residual solids, centrate N), which is consistent with highly degradable carbon rich substrates. Importantly, the model predicts that the biosolids would still meet the ASVR requirements in EoW codes under this operation.

Table 21 was generated using kinetic parameters from co-digestion experiments (Table 19) and assumes that each feed mixture degrades at a uniform rate which is impacted by mixture composition and GTW addition rate, this simulation may be more representative of short-term behaviours without acclimation to the waste mixture or step changes in loading rate. The results in Table 21 show higher methane production and lower biosolids production when compared to Table 20, this is due to the minor increases in process kinetics at low GTW addition rates. As GTW increases the process becomes overloaded resulting in slower kinetics. Methane is still improved under these high GTW load conditions but the biosolid product is much less stable, demonstrated by higher residual degradability and higher predicted AVSR. This higher residual degradability represents lost opportunity (degradable material represents methane potential), but also increases the risks around EoW compliance.

The import target for GTW at the host site corresponds to an increase in organic load of 18% and is not likely to exceed process limits.

Table 20: CSTR model examining the impact of GTW co-digestion at a Municipal WWTP (modelling using k_{hyd} and f_d parameters fitted to mono-digestion experiments in Table 19)

Parameters	Baseline	10% GTW	20% GTW	50% GTW	100% GTW	150% GTW
Sludge Load (m^3/d)	Commercial in Confidence					
GTW Load (m^3/d)	Commercial in Confidence					
SRT (d)	22.6	22.1	21.6	20.3	18.4	16.9
OLR-COD (kg/m^3.d)	2.8	3.07	3.35	4.2	5.6	7
OLR-VS (kg/m^3.d)	1.7	1.77	1.85	2.08	2.46	2.84
CH_4 Production (m^3/d)	1910	2241	2568	3533	5086	6551
Biosolid Production (ton/d)	31	31.4	32	34	37.4	41
Centrate N (kg/d)	237	246	255	278	309	335
Centrate P (kg/d)	77	80	82	88	95	101
Residual Degradability (% VS)	13.4	14.4	15.5	18.5	23.1	27.2
AVSR (%)	12.7	13.7	14.7	17.5	21.9	25.8
EoW Code	Pass	Pass	Pass	Risk	Fail	Fail

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Table 21: CSTR model examining the impact of GTW co-digestion at a Municipal WWTP (modelling using k_{hyd} and f_d parameters fitted to co-digestion experiments in Table 19 at the corresponding loading rate)

Parameters	Baseline	10% GTW	20% GTW	50% GTW	100% GTW	150% GTW
Sludge Load (m^3/d)			Commercial in Confidence			
GTW Load (m^3/d)			Commercial in Confidence			
SRT (d)	22.6	22.1	21.6	20.3	18.4	16.9
OLR-COD (kg/m^3.d)	2.8	3.07	3.35	4.2	5.6	7
OLR-VS (kg/m^3.d)	1.7	1.77	1.85	2.08	2.46	2.84
CH_4 Production (m^3/d)	1910	2342	2768	3268	5396	7156
Biosolid Production (ton/d)	31	30.3	29.9	33.7	33.4	35.3
Centrate N (kg/d)	237	266	291	283	366	407
Centrate P (kg/d)	77	86	94	90	113	123
Residual Degradability (% VS)	13.4	15.6	17.5	19.5	36.1	42.6
AVSR	12.7	14.8	16.6	18.5	34.3	40.5
EoW Code	Pass	Pass	Risk	Fail	Fail	Fail

3.5 Co-digestion Scenario 3: Import of Dairy and Milk Processing Waste to a Municipal WWTP treating Sewage Sludge and GTW

3.5.1 Scenario Development and Experimental Data

Co-digestion Scenario 3 is designed to build on Scenario 2 through the addition of Dairy Milk Processing Waste (DMP) to the sludge-GTW mixture. On an organic load basis, DMP was the second largest FIW stream imported to the host facility in 2023/24, although this stream represents a relatively minor fraction of target imports (~15% increase in organic load if added to a single digester or 3% if distributed across the 5 operating digesters). In this experiment, a sewage sludge and GTW mixture was considered as the base substrate (GTW at 10% of MSS to match 2023/24 import levels) and DMP was then added to provide additional organic load. DMP was added at 10, 20, 50, 100, 150, and 200% of the sludge + GTW COD load, these levels significantly exceed planned import rates but allow assessment of future commercial opportunities. Kinetic parameters from the DMP co-digestion experiment are summarized in Table 22 with methane production curves included in Appendix C. Similar to Co-digestion Experiment 2 the results show a progressive increase in methane production as DMP load increases which is again consistent the high energy potential and the relatively high biodegradability of the DMP in comparison to MSS.

The apparent hydrolysis rate (k_{hyd}) remained stable for DMP loads up to 50% but decreased for DMP addition of 100%. 150% and 200%. At DMP loads of 150% and 200%, the decrease in hydrolysis rate was significant and would have a substantial impact on biosolids product quality in a digester with a conventional SRT of 18-24 days. An extended lag period of 10 days was observed at a DMP loading rate of 200%, demonstrating a temporary overload scenario. The DMP waste comprised 16% of the reactor volume at start up of the 200% load experiment; when applied to a commercial digester, this volume far exceeds the availability of this material. The combined impacts of increased volume load, decreased treatment times and decreased process rates are explored using the CSTR model and presented in Table 23 and Table 24.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Table 22: Kinetic parameters estimated during batch co-digestion of DMP (with 95% CI).

Substrate	Delay Time *td* (d)	Apparent Hydrolysis Rate k_{hyd} (d^{-1})	Methane Potential *B0* (m^3 CH4/kg VS)	Degradable Fraction *fd* (Estimated by modelled co-digestion parameters)	Degradable Fraction *fd* (Estimated using mono-digestion parameters)
Mono-digestion					
PS		0.21 ± 0.04	480 ± 92	0.74 ± 0.04	
TWAS		0.11 ± 0.02	275 ± 142	0.53 ± 0.04	
GTW	11.5 ± 0.9	0.29 ± 0.11	905 ± 61	1 ± 0.06	
DW		0.18 ± 0.03	727 ± 45	0.87 ± 0.04	
PS + TWAS		0.20 ± 0.05	342 ± 67	0.59 ± 0.04	
PS + TWAS + GTW		0.22 ± 0.05	527 ± 62	0.60 ± 0.04	
Co-digestion					
+10% DW		0.21 ± 0.04	347 ± 55	0.57 ± 0.03	0.68 ± 0.07
+20% DW		0.23 ± 0.05	402 ± 62	0.64 ± 0.04	0.70 ± 0.07
+50% DW		0.23 ± 0.04	429 ± 52	0.65 ± 0.04	0.73 ± 0.08
+100% DW		0.17 ± 0.02	476 ± 43	0.68 ± 0.03	0.76 ± 0.08
+150% DW		0.10 ± 0.01	534 ± 41	0.74 ± 0.03	0.78 ± 0.08
+200% DW	10 ± 2	0.08 ± 0.02	632 ± 100	0.86 ± 0.08	0.79 ± 0.08

3.5.2 Model-based Assessment of Process Limits

This section summarises process performance predictions during co-digestion of DMP waste at a municipal treatment plant simulated using the CSTR model. The maximum DMP addition rate considered in this analysis was 50% of sludge organic load, higher dose rates were not considered due to the lower expected availability of DMP waste. Similar to Scenario 2, Table 23 was generated using kinetic parameters from mono-digestion experiments (Table 22) and Table 24 was generated using kinetic parameters from co-digestion experiments, the purpose of the replicate analysis was to explore both the short term (Table 23) and long term (Table 24) impacts of DMP addition.

While DMP is more concentrated than sewage sludge, it is dilute compared to other FIWs tested and as a result the volumes of DMP required to increase organic loads are much more significant. For example, addition of DMP at 10% of organic load requires 2-3 times the import volume of GTW or SFW. This increased volume has a clear impact on the CSTR model simulations. Results show that addition of DMP at just 10% of organic load would reduce the quality of the biosolids product and risk EoW compliance, therefore addition of DMP at 10% organic load may exceed process limits.

The import target for DMP at the host site corresponds to an increase in organic load of 3%. This addition rate would increase methane production by a small amount of around 5% (from 2241 m^3/d to 2350 m^3/d). The increase in centrate nitrogen and biosolids would also be small. Importantly, the model predicts that the biosolids would still meet the ASVR requirements in EoW codes under this operation.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Table 23: CSTR model examining the impact of DMP co-digestion at a Municipal WWTP (modelling using k_{hyd} and f_d parameters fitted to mono-digestion experiments in Table 22)

Parameters	Baseline	3% DMP	10% DMP	20% DMP	50% DMP
Sludge Load (m^3/d)	Commercial in Confidence				
GTW Load (m^3/d)	Commercial in Confidence				
DMP Load (m^3/d)	Commercial in Confidence				
SRT (d)	22.1	21.7	20.6	19.3	16.2
OLR-COD (kg/m^3.d)	3.1	3.2	3.4	3.7	4.6
OLR-VS (kg/m^3.d)	1.8	1.8	1.9	2.1	2.5
CH_4 Production (m^3/d)	2241	2350	2661	3070	4237
Biosolid Production (ton/d)	31.4	31.7	32.5	33.7	37.7
Centrate N (kg/d)	246	253	273	298	361
Centrate P (kg/d)	80	82	90	100	126
Residual Degradability (% of VS)	14.4	15.2	17.4	20.4	29.2
AVSR	13.7	14.6	16.5	19.4	27.7
EoW Code	Pass	Risk	Risk	Fail	Fail

Table 24: CSTR model examining the impact of DMP co-digestion at a Municipal WWTP (modelling using k_{hyd} and f_d parameters fitted to co-digestion experiments in Table 22)

Parameters	Baseline	3% DMP	10% DMP	20% DMP	50% DMP
Sludge Load (m^3/d)	Commercial in Confidence				
GTW Load (m^3/d)	Commercial in Confidence				
DMP Load (m^3/d)	Commercial in Confidence				
SRT (d)	22.1	21.7	20.6	19.3	16.2
OLR-COD (kg/m^3.d)	3.07	3.2	3.37	3.68	4.6
OLR-VS (kg/m^3.d)	1.77	1.8	1.92	2.08	2.54
CH_4 Production (m^3/d)	2241	N/A	2843	3500	4295
Biosolid Production (ton/d)	31.4	N/A	30.8	30.3	36.3
Centrate N (kg/d)	246	N/A	304	354	381
Centrate P (kg/d)	80	N/A	100	119	134
Residual Degradability (% of VS)	14.4	N/A	19.9	24.6	28.2
AVSR	13.8	N/A	18.9	23.4	25.8
EoW Code	Pass	N/A	Fail	Fail	Fail

3.6 Co-digestion Scenario 4: Import of Solid Food Waste to a Municipal WWTP treating a Mixture of Sewage Sludge, GTW, BEV and DMP Waste

3.6.1 Scenario Development and Data Used

Co-digestion Scenario 4 represents the target operating scenario at the host facility, where SFW is imported to a municipal co-digestion facility already processing a complex mixture of waste streams, including mixed sewage sludge, GTW, BEV and DMP waste. Scenario 4a was based on a facility operating with GTW, BEV, DMP loads matching the average imports to the host site during 2023/24. Scenario 4b increased the GTW, BEV, DMP loads to match the commercial targets of the host site. For each scenario the SFW was considered the variable co-substrate and was simulated at addition rates of 10%, 20% 34% and 50% of the sludge COD load (with 34% being the commercial target). Kinetic parameters used in the analysis were taken from mono-digestion control experiments previously described and summarized in Table.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Table 25: Kinetic parameters used to model co-digestion of mixed sludge, GTW, BEV, DMP waste and SFW in a continuous process (with 95% CI).

Substrate	Lag (days)	Apparent hydrolysis Rate (k_{hyd}):	Methane Potential (L/kgVS):	Degradable Fraction (L/kgVS):
Mixed Sludge		0.20 ± 0.04	262 ± 14	0.46 ± 0.03
GTW	12.3 ± 0.4	0.18 ± 0.03	834 ± 34	0.83 ± 0.04
BEV		0.24 ± 0.07	617 ± 40	0.80 ± 0.02
DMP		0.18 ± 0.03	727 ± 45	0.87 ± 0.04
SFW		0.29 ± 0.06	385 ± 16	0.79 ± 0.04

3.6.2 Model-based Assessment of Process Performance and Process Limits

Table 26 shows simulation results when SFW is imported to co-digestion facility operating with GTW, BEV, DMP loads that match the average imports to the host site during 2023/24. Simulations show that importing SFW at the target import load of 34% of the base organic load would increase methane by approximately 50% (from 2312 m^3/d to 3403 m^3/d) with a 20% increase in residual biosolids (31.6 tons/d to 37.8 tons/d), however the biosolid would be less stable representing EoW compliance risk.

Table 27 shows simulation results when SFW is imported to co-digestion facility operating with GTW, BEV, DMP loads that match the target imports to the host site. Simulations show that the base case (without importing SFW) is already approaching EoW compliance limits with a predicted AVSR of 16% (17% threshold). If SFW was imported at the target load of 34% of the base sludge load, the model predicts methane would increase approximately 40% (from 2764 m^3/d to 3838 m^3/d) with a 20% increase in residual biosolids, but with a predicted AVSR of 19.8% that does not meet EoW compliance.

Table 26: CSTR model examining the impact of importing SFW to a Municipal WWTP already treating GTW and DMP (average volumes recorded in 2023/24)

Parameters	Baseline	10% SFW	20% SFW	34% SFW	50% SFW
Sludge Load (m^3/d)			Commercial in Confidence		
GTW Load (m^3/d)			Commercial in Confidence		
BEV Load (m^3/d)			Commercial in Confidence		
DMP Load (m^3/d)			Commercial in Confidence		
SFW Load (m^3/d)			Commercial in Confidence		
SRT (d)	21.8	21.3	20.7	19.8	19.3
OLR-COD (kg/m^3.d)	3.1	3.4	3.6	4.1	4.3
OLR-VS (kg/m^3.d)	1.8	2.0	2.2	2.5	2.7
CH_4 Production (m^3/d)	2313	2602	2889	3403	3738
Biosolid Production (ton/d)	31.6	33.2	34.8	37.8	39.8
Centrate N (kg/d)	251	280	308	355	384
Centrate P (kg/d)	82	89	97	108	115
Residual Degradability (% of VS)	14.9	16.1	17.3	19.2	20.3
AVSR	14.2	15.3	16.4	18.2	19.3
EoW Code	Pass	Pass	Risk	Fail	Fail

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Table 27: CSTR model examining the impact of importing SFW to a Municipal WWTP already treating GTW and DMP (target import volumes)

Parameters	Baseline	10% SFW	20% SFW	34% SFW	50% SFW
Sludge Load (m^3/d)			Commercial in Confidence		
GTW Load (m^3/d)			Commercial in Confidence		
BEV Load (m^3/d)			Commercial in Confidence		
DMP Load (m^3/d)			Commercial in Confidence		
SFW Load (m^3/d)			Commercial in Confidence		
SRT (d)	20.7	20.1	19.7	18.9	18.4
OLR-COD (kg/m^3.d)	3.5	3.8	4.0	4.4	4.7
OLR-VS (kg/m^3.d)	1.9	2.1	2.3	2.6	2.9
CH_4 Production (m^3/d)	2764	3049	3332	3838	4168
Biosolid Production (ton/d)	32.8	34.5	36.1	39.1	41.2
Centrate N (kg/d)	268	295	321	367	396
Centrate P (kg/d)	87	94	101	112	119
Residual Degradability (% of VS)	16.8	17.8	19.0	20.8	21.9
AVSR	16.0	16.9	18.1	19.8	21.1
EoW Code	Risk	Risk	Fail	Fail	Fail

3.7 Evaluating the Impact of Co-digestion at a Municipal WWTP

This section assesses the impact of co-digestion at a municipal WWTP. The analysis considered 3 main factors: An economic evaluation (described in Section 2.6), an assessment of the plant energy balance and an assessment of the GHG impact (described in Section 2.7).

3.7.1 Economic Impact

Economic evaluations for the import SFW to municipal co-digestion facility are presented in Table 28 and Table 29, the evaluations cover scenarios where the co-digestion facility operates at import levels achieved in 2023/24 (Table 28) and if the long-term target import levels are achieved (Table 29). The economic assessment indicates that the current economic benefit from co-digestion is $212 per day or $77,000 per year, without considering gate fees or trade waste charges (orange in Tables). Interestingly, the analysis shows that if SFW was imported to the facility at the target rate (blue in table), there would be a net economic cost of $57/day or $20,000 per year, this decline in economic performance is attributed to the reduced waste conversion that occurs as process loading rates increase and is consistent with the diminishing returns reported previously (Jensen and Tait, 2018). The CSTR model indicated that the maximum safe import level of SFW (at current FIW dosing) was 20% of base sludge organic load, economic analysis indicates a net economic benefit would occur at this import rate (green in table).

Table 29 explores the potential future impact on process economics if the co-digestion facility reaches import targets for FIW waste streams. If the facility was to achieve import targets without adding SFW, the assessment estimates that the economic benefit $370/d ($135,000/yr), this was the best economic performance of any scenario testing and CSTR modelling indicates this is within defined process limits. Addition of SFW generally decreased the economic benefit, this impact was attributed to a combination of the residual solids after digestion and the relatively large amount of nitrogen present in the SFW tested, as a result the costs of managing the digestate residue was larger than the value of the extra biogas. However, if SFW was added at 10% of sludge organic load (the maximum level within defined process limits), there is still a clear net benefit from co-digestion at approx. $100,000/yr ($287/d). It's important to note that these economic outcomes could change significantly if the cost of biosolids management was to change.

Table 28 Economic Evaluation for Import of SFW to a WTP co-digestion facility (operating under Import loads from 2023/24)

Parameters	Baseline	0% SFW	10% SFW	20% SFW	34% SFW	50% SFW
Case Summary						
Sludge Load (m^3/d)			Commercial in Confidence			
GTW Load (m^3/d)			Commercial in Confidence			
BEV Load (m^3/d)			Commercial in Confidence			
DMP Load (m^3/d)			Commercial in Confidence			
SFW Load (m^3/d)			Commercial in Confidence			
CH_4 Production (m^3/d)	1910	**2313**	2602	2889	3403	3738
Biosolid Production (ton/d)	31	**31.6**	33.2	34.8	37.8	39.8
Centrate N (kg/d)	237	**251**	280	308	355	385
Centrate P (kg/d)	77	**82**	89	97	108	115
Economics						
Methane Value ($/d)	$1,613	**$1,953**	$2,197	$2,440	$2,874	$3,157
Solids Disposal Cost ($/d)	-$4,650	**-$4,740**	-$4,980	-$5,220	-$5,670	-$5,970
Centrate N Cost ($/d)	-$474	**-$502**	-$560	-$616	-$710	-$770
Centrate P Cost ($/d)	-$154	**-$164**	-$178	-$194	-$216	-$230
Total Operating Cost ($/d)	-$3,665	**-$3,453**	-$3,521	-$3,590	-$3,722	-$3,813
Total compared to baseline ($/d)	-	**$212**	$144	$75	-$57	-$148

Table 29 Economic Evaluation for Import of SFW to a WWTP co-digestion facility (operating at target import loads from 2023/2024)

Parameters	Baseline	0% SFW	10% SFW	20% SFW	34% SFW	50% SFW
Case Summary						
Sludge Load (m^3/d)			Commercial in Confidence			
GTW Load (m^3/d)			Commercial in Confidence			
BEV Load (m^3/d)			Commercial in Confidence			
DMP Load (m^3/d)			Commercial in Confidence			
SFW Load (m^3/d)			Commercial in Confidence			
CH_4 Production (m^3/d)	1910	**2764**	**3049**	**3332**	**3838**	**4168**
Biosolid Production (ton/d)	31	**32.8**	34.5	36.1	**39.1**	41.2
Centrate N (kg/d)	237	**268**	295	321	**367**	396
Centrate P (kg/d)	77	**87**	94	101	**112**	119
Economics						
Methane Value ($/d)	$1613	$2334	$2575	$2814	**$3241**	$3520
Solids Disposal Cost ($/d)	-$4650	-$4920	-$5175	-$5415	**-$5865**	-$6180
Centrate N Cost ($/d)	-$474	-$536	-$590	-$642	**-$734**	-$792
Centrate P Cost ($/d)	-$154	-$174	-$188	-$202	**-$224**	-$238
Total Operating Cost ($/d)	-$3665	-$3296	-$3378	-$3445	**-$3582**	-$3690
Total compared to baseline ($/d)	0	$369	$287	$220	**$83**	-$25

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

3.7.2 Impact on WWTP Energy Balance

Evaluations of the Plant Energy Balance when SFW is imported to a municipal co-digestion facility are presented in Table 30 and Table 31, the evaluations cover scenarios where the co-digestion facility operates at import levels achieved in 2023/24 (Table 30) and if the long-term target import levels are achieved (Table 31). During the analysis period where the facility was importing GTW and DMP at 2023/2024 levels (orange in Tables), the assessment estimates that the onsite energy production was 23% higher compared with a sludge only base case. From interviews at the host site, approximately 60% of site energy requirements are currently supplied by biogas. If SFW was imported to the facility at the target rate of 34% or base sludge load (blue in table), the resulting improvement in onsite energy production would be 83% and may be enough to achieve energy self-sufficiency at the site, however the CSTR model suggested that operating at this dose level may exceed plant limits, due to EoW stability compliance. Importing SFW at only 20% of sludge organic load was modelled as being within process limits and this could result in 55% improvement in energy production compared to the base case or a 25% improvement compared to current operations. This will significantly reduce reliance on external energy, but would not make the plant self-sufficient.

Table 30 Energy Impacts from Import of SFW to a WTP co-digestion facility (operating under Import loads from 2023/24)

Parameters	Baseline	0% SFW	10% SFW	20% SFW	34% SFW	50% SFW
Sludge Load (m^3/d)	Commercial in Confidence					
GTW Load (m^3/d)	Commercial in Confidence					
BEV Load (m^3/d)	Commercial in Confidence					
DMP Load (m^3/d)	Commercial in Confidence					
SFW Load (m^3/d)	Commercial in Confidence					
CH_4 Production (m^3/d)	1910	2313	2602	2889	3403	3738
Biosolid Production (ton/d)	31	31.6	33.2	34.8	37.8	39.8
Centrate N (kg/d)	237	251	280	308	355	385
Centrate P (kg/d)	77	82	89	97	108	115
Energy Balance						
Methane Energy (MJ/d)	72580	87894	98876	109782	129314	142044
Methane Energy (kWh/d)	8064	9766	10986	12198	14368	15783
Centrate Aeration (kWh/d @ 2.5 kWh/kgN)	-592.5	-627.5	-700	-770	-887.5	-962.5
Dewatering Energy (@10kWh per wet ton)	-310	-316	-332	-348	-378	-398
Net Energy of Solids Train (kWh/d)	7162	8823	9954	11080	13103	14422
Energy Compared to Baseline (kWh/d)	0	1661	2792	3918	5941	7260
Improvement (%)	0	23.2	39.0	54.7	82.9	101.4

Table 31 explores the potential future impact on energy production if the co-digestion facility reaches import targets for FIW waste streams. If the facility was to achieve import targets without adding SFW, the assessment estimates that the production of renewable energy would increase to 10.6 MWh.d representing a 50% improvement over the base case (no FIW imports) and a 20% improvement over operation in 2023/24. If SFW was imported to the facility at the target rate of 34% or sludge organic load (blue in table), the corresponding energy production would be 15 MWh.d representing a ~100% improvement over the base case (no FIW imports) and a 70% improvement over current operations, however a SFW import rate of 10% of sludge organic load was identified as the maximum dosing to stay within process limits for this scenario. Energy production when the SFW import rate is 10% of sludge organic load is predicted at 11.8 MWh/d, a 34% improvement over current energy production predictions.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Table 31 Energy Impacts for Import of SFW to a WWTP co-digestion facility (operating at target import loads)

Parameters	Baseline	0% SFW	10% SFW	20% SFW	34% SFW	50% SFW
Sludge Load (m^3/d)	Commercial in Confidence					
GTW Load (m^3/d)	Commercial in Confidence					
BEV Load (m^3/d)	Commercial in Confidence					
DMP Load (m^3/d)	Commercial in Confidence					
SFW Load (m^3/d)	Commercial in Confidence					
CH_4 Production (m^3/d)	1910	**2764**	**3049**	**3332**	**3838**	**4168**
Biosolid Production (ton/d)	31	**32.8**	34.5	36.1	39.1	41.2
Centrate N (kg/d)	237	**268**	295	321	367	396
Centrate P (kg/d)	77	**87**	94	101	112	119
Energy Balance						
Methane Energy (MJ/d)	72580	105032	115862	126616	145844	158384
Methane Energy (kWh/d)	8064	11670	12874	14068	16205	17598
Centrate Aeration (kWh/d @ 2.5 kWh/kgN)	-592.5	-670	-737.5	-802.5	-917.5	-990
Dewatering Energy (@10kWh per wet ton)	-310	-328	-345	-361	-391	-412
Net Energy of Solids Train (kWh/d)	7162	10672	11791	12905	14896	16196
Energy Compared to Baseline (kWh/d)	0	3510	4629	5743	7734	9034
Improvement (%)	0	49.0	64.6	80.2	108.0	126.1

3.7.3 Impact on Greenhouse Gas (GHG) Emissions

The impacts on greenhouse gas emissions from importing SFW to a municipal co-digestion facility are presented in Table 32 and Table 33, the evaluations cover scenarios where the co-digestion facility operates at import levels achieved in 2023/24 (Table 32) and if the long-term target import levels are achieved (Table 33). During the analysis period where the facility was importing GTW and DMP at 2023-2024 level (orange in Tables), the assessment estimates that the co-digestion activities would have reduce GHG emissions from approximately 15 tons CO_2-e per day, with 93% of this benefit due to redirecting wastes from landfill. If SFW was imported to the facility at the target rate of 34% of sludge organic load (blue in table), the resulting reduction in GHG emissions could be approximately 68 tons/d CO_2-e, however the CSTR model suggested that operating at this dose level may exceed plant limits, due to EoW stability compliance. However, the CSTR model indicated that importing SFW at 20% of sludge organic load was within process limits and this could result in a GHG reduction of over 42 ton/d CO_2-e (green in table).

Table 33 explores the potential future impact on GHG emissions if the co-digestion facility reaches import targets for FIW waste streams. If the facility was to achieve import targets without adding SFW, the assessment estimates that the GHG reduction would be approximately 47 tons CO_2-e per day, with 96% of this benefit due to redirecting wastes from landfill. If SFW was imported to the facility at the target rate of 34% of sludge organic load (blue in table), the resulting reduction in GHG emissions could be approximately 86 tons/d CO_2-e, however the CSTR model suggested that operating at this dose level may exceed plant limits, due to EoW stability compliance. However, the CSTR model indicated that importing SFW at a lower level of 10% of sludge organic load was within process limits for this scenario and could result in a GHG reduction of over 47 ton/d CO_2-e (green in table). This represents a 300% improvement when compared to current GHG impact (45 ton per day potential impact, comparted to 15 ton/d current impact).

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

Table 32 GHG Impacts from Import of SFW to a WTP co-digestion facility (operating under Import loads from 2023/24)

Parameters	Baseline	0% SFW	10% SFW	20% SFW	34% SFW	50% SFW
Sludge Load (m^3/d)	Commercial in Confidence					
GTW Load (m^3/d)	Commercial in Confidence					
BEV Load (m^3/d)	Commercial in Confidence					
DMP Load (m^3/d)	Commercial in Confidence					
SFW Load (m^3/d)	Commercial in Confidence					
CH_4 Production (m^3/d)	1910	2313	2602	2889	3403	3738
Net Energy of Solids Train (kWh/d)	7162	8823	9954	11080	13103	14422
Emissions Reduction						
Scope 1 Emissions from Energy Production using Biogas ($kgCO_2$-e/d)	467	565	636	706	831	913
Scope 1 Emissions from Anaerobic Digestion of wastes ($kgCO_2$-e/d)	6440	6667	6843	7020	7339	7549
Scope 2 Savings from Reduction in Purchased Electricity ($kgCO_2$-e/d)	-5403	-6543	-7361	-8173	-9627	-10574
Scope 3 Savings from Reduction in Purchased Electricity ($kgCO_2$-e/d)	-726	-879	-989	-1098	-1293	-1420
Scope 3 Emissions Avoided by Redirecting Waste from Landfill ($kgCO_2$-e/d)	0	-13965	-27195	-40425	-64365	-80115
Emissions credited to Solids Train ($kgCO_2$-e/d)	778	-14155	-28066	-41970	-67115	-83648
Emissions compared to Baseline ($kgCO_2$-e/d)	0	-14933	-28843	-42748	-67892	-84425

Table 33 GHG Impacts from Import of SFW to a WWTP co-digestion facility (operating at target import loads)

Parameters	Baseline	0% SFW	10% SFW	20% SFW	34% SFW	50% SFW
Sludge Load (m^3/d)	Commercial in Confidence					
GTW Load (m^3/d)	Commercial in Confidence					
BEV Load (m^3/d)	Commercial in Confidence					
DMP Load (m^3/d)	Commercial in Confidence					
SFW Load (m^3/d)	Commercial in Confidence					
CH_4 Production (m^3/d)	1910	2764	3049	3332	**3838**	4168
Net Energy of Solids Train (kWh/d)	7162	10672	11791	12905	**14896**	16196
Emissions Reduction						
Scope 1 Emissions from Energy Production using Biogas ($kgCO_2$-e/d)	467	675	745	814	938	1018
Scope 1 Emissions from Anaerobic Digestion of wastes ($kgCO_2$-e/d)	6440	7227	7227	7403	7722	7932
Scope 2 Savings from Reduction in Purchased Electricity ($kgCO_2$-e/d)	-5403	-7819	-8625	-9426	-10857	-11791
Scope 3 Savings from Reduction in Purchased Electricity ($kgCO_2$-e/d)	-726	-1050	-1159	-1266	-1458	-1584
Scope 3 Emissions Avoided by Redirecting Waste from Landfill ($kgCO_2$-e/d)	0	-45360	-45360	-58590	-82530	-98280
Emissions credited to Solids Train ($kgCO_2$-e/d)	778	-46327	-47172	-61065	-86186	-102704
Emissions compared to Baseline ($kgCO_2$-e/d)	0	-47105	-47950	-61842	-86963	-103482

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

4. Conclusions & Recommendations

Target Food Industry Wastes in this project included Macerated Solid Food Waste (SFW), Grease Trap Waste (GTW), Beverage Processing Waste (BEV) and waste from Dairy and Milk Processing (DMP).

- GTW was the most concentrated waste steam tested, with the highest methane potential at 72 m^3/wet ton corresponding to 2.45 GJ/ton heat energy (compared to sewage sludge 10 m^3/wet ton, as added to the current AD process). The composition of GTW results in a large increase in biogas energy (revenue) with little corresponding increase in N or P treatment costs. GTW is largely a liquid waste stream and is not expected to pose any significant material handling challenges within the recycled centrate, as a result co-treatment of GTW does not rely on additional fees to be economically viable. The primary issue with GTW is the high variability in COD concentrations, which varied from 91 g/L up to 375 g/L between tanker loads. This variability can lead to increased fluctuations in the organic loading to the digesters which result in transient behaviors that must be managed.
- SFW was the second most concentrated waste stream tests with methane potential at 64 m^3/wet ton corresponding to 2.2 GJ/ton heat energy (compared to sewage sludge 10 m^3/wet ton, as added to the current AD process). At smaller scale, food waste was reported to be highly variable, attributed to variations waste timings that result in different ratios of meat, dairy, fresh produce and baked goods within the mix. However at larger scale these differences appeared to even out and the composition of bulk macerated food waste appeared much less variable. SFW had poor flow properties and was more difficult to handle at the concentrations received, it may be necessary to dilute the SFW in order to manage process loading at the levels required for full scale implementation. SFW contained much higher concentrations of N and P and increased the mass of residual solids for disposal, co-treatment of SFW requires a gate fee or service charge to be economically viable.
- DMP and BEV were less concentrated with methane potential of 34 m^3/wet ton and 29 m^3/wet ton respectively. These wastes were highly soluble and easy to manage, however the lower strength of these wastes suggests that limited increases in organic load can be achieved without exceeding the volume loading limits of existing digesters. The low strength may also increase the relative transport costs to import these co-substrates to site.

The pilot-scale test facility was operated for over 400 days and examined co-substrate loadings from 10% of organic load up to 50% of organic load. The pilot scale test work was largely successful in validating the laboratory results as a predictor of steady state behaviour at larger scale, this work demonstrates:

- In general, the methane production from the test facility was similar to the performance model predictions, while the solids destruction performance exceeded the lab-based performance models.
- Biogas production in the test facility was highly dynamic and was impacted by both the co-substrate loading strategy and the digester mixing strategy. Depending on co-substrate loading strategy, dynamic biogas production rates varied from approximately 50 to over 250 L/m^3/hr over a typical 24-hour cycle. Monitoring changes in daily biogas production does not capture the dynamic impacts of co-treatment and continuous gas monitoring is essential to ensure gas handling limits are not exceeded.
- When assessing the relative impact of co-substrate loading and digester mixing:
    - There was a short-term increase in biogas production after addition of a food industry waste spike. The increase in biogas rate initially increased as the size of the FIW dosed increased, but reached a maximum of 35% and was

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

attributed to a biological limit. Further work is required to assess whether the biological capacity of the system will increase through acclimation.

- The impact of cyclic mixing events was variable and seemed to be greater in the periods after the pilot was fed, with biogas production rates varying by up to 100% between mixing-ON and mixing-OFF phases.
- Biogas production peaked approximately 1 hr after a spike dose of food industry waste and while the digester was being mixed. Monitoring biogas production during this period is essential to determining the maximum gas handling requirements.

The digestate product was collected from the pilot test facility at multiple time points and assessed for reuse potential against the current End of Waste codes in Queensland. Key learnings are:

- The Food Industry Wastes examined in this project contained significantly lower heavy metal concentrations when compared to mixed sewage sludge, which had a dilution effect and resulted in lower contaminant levels in the resulting digestate. At the FIW addition rates, the contaminant dilution effect may be enough to shift the Class of biosolid from Contaminant Grade C to Contaminant Grade B, opening up additional reuse options (subject to an appropriate pathogen reduction step).
- Co-treatment of food industry waste had a negative waste impact on the biosolids stability, measured using Additional Volatile Solids Reduction (AVSR), but the level of impact was also transient. The pilot plant operates with a simultaneous feeding and wasting strategy, which is common practice for commercial anaerobic digesters. Simultaneous feeding/wasting increases the risk of short-circuiting during feed events where feed material bleeds through the system without correct treatment. Short-circuiting during feed events can result in digestate that fails EoW stability tests for a period of time, further testing is required to assess mixing dynamics in the reactor, the extent of short-circuiting and the period of EoW non-compliance that may occur during large feed events.
- The maximum safe import load of food industry waste imported is dependant on the type of food industry wastes in the mixture.
- If the host facility remains at current import loads of GTW, BEV and DMP, then performance models show SFW could be imported at up to 20% of sludge organic load without exceeding process limits.
- If the host facility reaches target import loads of GTW, BEV and DMP, then performance models show that the mass of SFW that can be imported without exceeding process limits decrease to 10% of sludge organic load.

Co-treatment of food waste at municipal sewage treatment plants was confirmed as a promising strategy to valorise food waste, reduce environmental footprints of waste management and boost renewable energy production.

- Approximately 60% of energy requirements supplied by biogas at the host site. If SFW was imported to the facility at the target rate of 34% of sludge organic load, the resulting improvement in onsite energy production would be 50% (i.e. from 60% to 90%) and may be enough to achieve energy self-sufficiency at the site is energy use is optimised, however the CSTR model suggested that operating at this dose level may exceed product quality limits. Importing SFW at 20% of sludge load was modelled as being within process limits and this could result in 26% improvement in energy production (i.e. from 60% to 76%). This will significantly reduce reliance on external energy, but would not make the plant self-sufficient.
- The project demonstrates that future GHG avoidance of 15,000 t CO_2-e per year could be achieved at a single large WWTP in the future, without compromising existing plant operations. This impact could be expanded to multiple WWTP of similar size, already existing in large population centres throughout Australia. Broad uptake of project outcomes and co-digestion strategies throughout Australia could result in annual GHG reductions of over 200,000 tonnes per year.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

5. Impact and Ongoing Monitoring

5.1 Economic Impact

Economic impacts for the project were assessed in Section 3.7.1, these assessments did not present all economic factors due to commercial considerations. There are four main considerations when assessing the economic impact of project activities:

i) Costs of treating the Food Industry Waste at the WWTP (sensitive to nitrogen and phosphorus content)

ii) Costs of managing the increase in residual biosolids (sensitive to the non-digestible solids content)

iii) Revenue from renewable energy produced (sensitive to the digestible fraction)

iv) Revenue from commercial charges applied to waste generators (waste dependant and not considered in this project)

Note: Costs of transporting Food Industry Waste to the Municipal WWTP is an additional factor but as this replaces existing costs of transporting the wastes to landfill or compost facilities these costs have not been considered.

Project analysis demonstrates that economics of importing and co-treating Food Industry Wastes are highly dependent on the type of food waste. For liquid food industry wastes the economic benefit to the WWTP (from biogas) exceeds the treatment cost meaning the activity doesn't rely on gate fees to be profitable. However, economic analysis suggests importing solid food waste would result in a net cost to the WWTP, where the costs of managing the increased solids residues (biosolids) and nutrients exceed the value of the additional biogas energy by a marginally amount. When importing Solid Food Waste to a WWTP a gate fee is likely required to make the activity profitable for the utility. Gate fees and service charges are common practice for landfills and other solid waste disposal facilities and if a nominal gate fee of $113 per t (landfill disposal of clean green waste, BCC 2026) was applied to a target solid waste import load equal to 34% of the sludge organic load the resulting income would exceed $1M per year. Although this figure may impact process stability.

Impacts from this project will continue beyond the project life due to new and existing commercial arrangements that cover the continued import of Food Industry Wastes to municipal wastewater treatment plants operated by the project partner group. It is important to note that economic impacts will be highly sensitive to regulations on the end use of biosolids and the commercial cost of biosolids management.

5.2 Impact on Greenhouse Gas Emissions

This project impacts greenhouse gas emissions through two key mechanisms: i) food waste is diverted from emission intensive management strategies, such as landfilling and ii) food waste is used to generate renewable energy, which offsets emissions from fossil derived electricity. Section 3.7.3 provides a detailed assessment of GHG impacts achieved during the life of the project and projections for future impacts. As an example of impact achieved during the project, the industry partner imported approximately 8 t/d of food industry waste to the full scale anaerobic digesters, the resulting renewable energy from this activity results in an estimated GHG saving of 2340 t/y (Scope 2). Impact of Scope 3 emissions is more challenging to calculate as there are multiple waste management strategies that may have been used to process this waste prior to the project (i.e. sewer, composting, landfill), however

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

if this material had been redirected from landfill, the GHG saving would be estimated at 1-2 per t-CO_2-e per t waste, corresponding to 5,000 t/y of CO_2-e avoidance and a total impact of close to 7,400 t/y.

Impacts from this project will continue beyond the project life due to new and existing commercial arrangements that cover the continued import of Food Industry Wastes to municipal wastewater treatment plants operated by the project partner group. Waste import levels are expected to expand, in part due to knowledge gained in the project, which will further increase the GHG impacts resulting from import activities. The project demonstrates that future impacts of 47 t CO_2-e per day corresponding to 15,000 t CO_2-e per year could be achieved at a single large WWTP in the future, without compromising existing plant operations. This impact could be expanded to multiple WWTP of similar size, already existing in large population centres throughout Australia. Broad uptake of project outcomes and co-digestion strategies throughout Australia could result in annual GHG reductions of over 200,000 tonnes per year.

5.3 Training Impact

A summary of students supported by the project is presented in Table 34.

Table 34 Summary of Students who Contributed to Project

Position	Focus Area/Title	Graduated
Thesis Project: MSc. in Environmental Engineering	Waste to Energy: Fuelling Sustainable Wastewater Treatment with Food Waste: A Case Study on [REDACTED] WWTP	Yes
Thesis Project:	Importing Trade Waste to Enhance Production of Renewable Energy at STP: Predicting Bottlenecks and Plant Limits	Yes
PhD student (Partial Contribution to Project)	The role of conductive materials in propionate degradation during anaerobic digestion	Yes

6. Acknowledgements

This work has been supported by Urban Utilities and End Food Waste Cooperative Research Centre whose activities are funded by the Australian Government's Cooperative Research Centre Program. This is EFW CRC Document 2026/019

7. References

ABDESHAHIAN, P., LIM, J. S., HO, W. S., HASHIM, H. & LEE, C. T. 2016. Potential of biogas production from farm animal waste in Malaysia. *Renewable and Sustainable Energy Reviews,* 60**,** 714-723.

AHRING, B. K., SANDBERG, M. & ANGELIDAKI, I. 1995. Volatile fatty acids as indicators of process imbalance in anaerobic digestors. *Applied Microbiology and Biotechnology,* 43**,** 559-565.

AL SEADI, T., RUTZ, D., JANSSEN, R. & DROSG, B. 2013. Biomass resources for biogas production. *In:* WELLINGER, A., MURPHY, J. & BAXTER, D. (eds.) *The biogas handbook : science, production and applications.* Oxford: Oxford : Woodhead Publishing.

ANGELIDAKI, I., ALVES, M., BOLZONELLA, D., BORZACCONI, L., CAMPOS, J. L., GUWY, A. J., KALYUZHNYI, S., JENICEK, P. & VAN LIER, J. B. 2009a. Defining the Biomethane Potential (BMP) of Solid Organic Wastes and Energy Crops: a Proposed Protocol for Batch Assays. *Water Science & Technology***,** 927-934.

ANGELIDAKI, I., ALVES, M., BOLZONELLA, D., BORZACCONI, L., CAMPOS, J. L., GUWY, A. J., KALYUZHNYI, S., JENICEK, P. & VAN LIER, J. B. 2009b. Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays. *Water Science and Technology,* 59**,** 927.

APHA 2012. Standard Methods for the Examination of Water and Wastewater, 22nd ed. . Washington, DC: American Public Health Association.

BATSTONE, D. J., KELLER, J., ANGELIDAKI, I., KALYUZHNYI, S. V., PAVLOSTATHIS, S. G., ROZZI, A., SANDERS, W. T., SIEGRIST, H. & VAVILIN, V. A. 2002. The IWA Anaerobic Digestion Model No 1 (ADM1). *Water Science and Technology,* 45**,** 65-73.

CHEN, Y., CHENG, J. J. & CREAMER, K. S. 2008. Inhibition of anaerobic digestion process: A review. *Bioresource Technology,* 99**,** 4044-4064.

CONRAD, R. 2005. Quantification of methanogenic pathways using stable carbon isotopic signatures: A review and a proposal. *Organic Geochemistry,* 35**,** 739-752.

DCCEEW 2025. Australian National Greenhouse Accounts Factors. Canberra, ACT.

DEMIREL, B. & SCHERER, P. 2008. The roles of acetotrophic and hydrogenotrophic methanogens during anaerobic conversion of biomass to methane: A review. *Reviews in Environmental Science and Biotechnology,* 7**,** 173-190.

FARRELL, J. B., BHIDE, V. & SMITH JR, J. E. 1996. Development of EPA's new methods to quantify vector attraction of wastewater sludges. *Water Environment Research,* 68**,** 286-294.

FIAL 2021. The National Food Waste Strategy Feasibility Study - Final Report.

FRANSON, M. A. H., EATON, A. D., ASSOCIATION., A. P. H., ASSOCIATION., A. W. W. & FEDERATION., W. E. 2005. *Standard methods for the examination of water & wastewater,* Washington, DC :, American Public Health Association.

HOLLIGER, C., ALVES, M., ANDRADE, D., ANGELIDAKI, I., ASTALS, S., BAIER, U., BOUGRIER, C., BUFFIÈRE, P., CARBALLA, M., DE WILDE, V., EBERTSEDER, F., FERNÁNDEZ, B., FICARA, E., FOTIDIS, I., FRIGON, J.-C., DE LACLOS, H. F., GHASIMI, D. S. M., HACK, G., HARTEL, M., HEERENKLAGE, J., HORVATH, I. S., JENICEK, P., KOCH, K., KRAUTWALD, J., LIZASOAIN, J., LIU, J., MOSBERGER, L., NISTOR, M., OECHSNER, H., OLIVEIRA, J. V., PATERSON, M., PAUSS, A., POMMIER, S., PORQUEDDU, I., RAPOSO, F., RIBEIRO, T., RÜSCH PFUND, F., STRÖMBERG, S., TORRIJOS, M., VAN EEKERT, M., VAN LIER, J., WEDWITSCHKA, H. & WIERINCK, I. 2016. Towards a standardization of biomethane potential tests. *Water Science and Technology,* 74**,** 2515-2522.

IACOVIDOU, E., OHANDJA, D.-G. & VOULVOULIS, N. 2012. Food waste co-digestion with sewage sludge – Realising its potential in the UK. *Journal of Environmental Management,* 112**,** 267-274.

JENSEN, P. & TAIT, S. 2018. Enhanced Energy Recovery in Australian Industry through Anaerobic Co-digestion.

JENSEN, P. D., ASTALS, S., BAI, X., NIERADZIK, L., WARDROP, P., BATSTONE, D. J. & CLARKE, W. P. 2022. Established full-scale applications for energy recovery from water: anaerobic digestion. London, United Kingdom: IWA Publishing.

KHALIL, M., BERAWI, M. A., HERYANTO, R. & RIZALIE, A. 2019. Waste to energy technology: The potential of sustainable biogas production from animal waste in Indonesia. *Renewable and Sustainable Energy Reviews,* 105**,** 323-331.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

KOCH, K., HELMREICH, B. & DREWES, J. E. 2015. Co-digestion of food waste in municipal wastewater treatment plants: Effect of different mixtures on methane yield and hydrolysis rate constant. *Applied Energy,* 137**,** 250-255.

KOPP, J. & DICHTL, N. 2000. Prediction of full-scale dewatering results by determining the water distribution of sewage sludges. *Water Science and Technology,* 42**,** 141-149.

LESTEUR, M., BELLON-MAUREL, V., GONZALEZ, C., LATRILLE, E., ROGER, J., JUNQUA, G. & STEYER, J. 2010. Alternative methods for determining anaerobic biodegradability: a review. *Process Biochemistry,* 45**,** 431-440.

LI, J., BAN, Q., ZHANG, L. & JHA, A. K. 2012. Syntrophic Propionate Degradation in Anaerobic Digestion: A Review. *International Journal of Agriculture and Biology,* 14**,** 843-850.

MACINTOSH, C. L. 2020. *Anaerobic co-digestion: micro to full-scale.* The University of Queensland, School of Chemical Engineering.

MATA-ALVAREZ, J., DOSTA, J., ROMERO-GÜIZA, M. S., FONOLL, X., PECES, M. & ASTALS, S. 2014. A critical review on anaerobic co-digestion achievements between 2010 and 2013. *Renewable and Sustainable Energy Reviews,* 36**,** 412-427.

MCINERNEY, M. J., STRUCHTEMEYER, C. G., SIEBER, J., MOUTTAKI, H., STAMS, A. J. M., SCHINK, B., ROHLIN, L. & GUNSALUS, R. P. 2008. Physiology, Ecology, Phylogeny, and Genomics of Microorganisms Capable of Syntrophic Metabolism. *Annals of the New York Academy of Sciences,* 1125**,** 58-72.

MURATÇOBANOĞLU, H., GÖKÇEK, Ö. B., MERT, R. A., ZAN, R. & DEMIREL, S. 2020. Simultaneous synergistic effects of graphite addition and co-digestion of food waste and cow manure: Biogas production and microbial community. *Bioresource Technology,* 309**,** 123365.

OLADEJO, O. S., DAHUNSI, S. O., ADESULU-DAHUNSI, A. T., OJO, S. O., LAWAL, A. I., IDOWU, E. O., OLANIPEKUN, A. A., IBIKUNLE, R. A., OSUEKE, C. O., AJAYI, O. E., OSUEKE, N. & EVBUOMWAN, I. 2020. Energy generation from anaerobic co-digestion of food waste, cow dung and piggery dung. *Bioresource Technology,* 313**,** 123694.

PARANJPE, A., SAXENA, S. & JAIN, P. 2023. A Review on Performance Improvement of Anaerobic Digestion Using Co-Digestion of Food Waste and Sewage Sludge. *Journal of Environmental Management,* 338**,** 117733.

QU, X., MAZÉAS, L., VAVILIN, V. A., EPISSARD, J., LEMUNIER, M., MOUCHEL, J.-M., HE, P.-J. & BOUCHEZ, T. 2009. Combined monitoring of changes in δ13CH4 and archaeal community structure during mesophilic methanization of municipal solid waste. *FEMS Microbiology Ecology,* 68**,** 236-245.

RIPLEY, L. E., BOYLE, W. C. & CONVERSE, J. C. 1986. Improved alkalimetric monitoring for anaerobic digestion of high-strength wastes. *Journal of the Water Pollution Control Federation,* 58**,** 406-411.

SANDERS, W., GEERINK, M., ZEEMAN, G. & LETTINGA, G. 2000. Anaerobic hydrolysis kinetics of particulate substrates. *Water Science and Technology,* 41**,** 17-24.

STRÄUBER, H., SCHRÖDER, M. & KLEINSTEUBER, S. 2012. Metabolic and microbial community dynamics during the hydrolytic and acidogenic fermentation in a leach-bed process. *Energy, Sustainability and Society,* 2**,** 13.

TAIT, S., TAMIS, J., EDGERTON, B. & BATSTONE, D. J. 2009. Anaerobic digestion of spent bedding from deep litter piggery housing. *Bioresource Technology,* 100**,** 2210-2218.

TCHOBANOGLOUS, G., STENSEL, H. D., TSUCHIHASHI, R., BURTON, F. L., ABU-ORF, M., BOWDEN, G. & PFRANG, W. 2014. *Wastewater engineering : treatment and resource recovery,* New York, NY, McGraw-Hill Education.

WANG, P., WANG, H., QIU, Y., REN, L. & JIANG, B. 2018. Microbial characteristics in anaerobic digestion process of food waste for methane production–A review. *Bioresource Technology,* 248**,** 29-36.

WICKHAM, R., GALWAY, B., BUSTAMANTE, H. & NGHIEM, L. D. 2016. Biomethane potential evaluation of co-digestion of sewage sludge and organic wastes. *International Biodeterioration & Biodegradation,* 113**,** 3-8.

ZHAO, K., WEI, Q., ZHANG, X., LIU, Y. & LI, F. 2024. Anaerobic co-digestion of food waste and excess sludge by humus composites: Characteristics and microbial community structure. *Journal of Environmental Chemical Engineering,* 12**,** 113673.

ZHOU, M., YAN, B., WONG, J. W. C. & ZHANG, Y. 2018. Enhanced volatile fatty acids production from anaerobic fermentation of food waste: A mini-review focusing on acidogenic metabolic pathways. *Bioresource Technology,* 248**,** 68-78.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

APPENDIX A –Methane Production Curves from Co-digestion of SFW at a WWTP

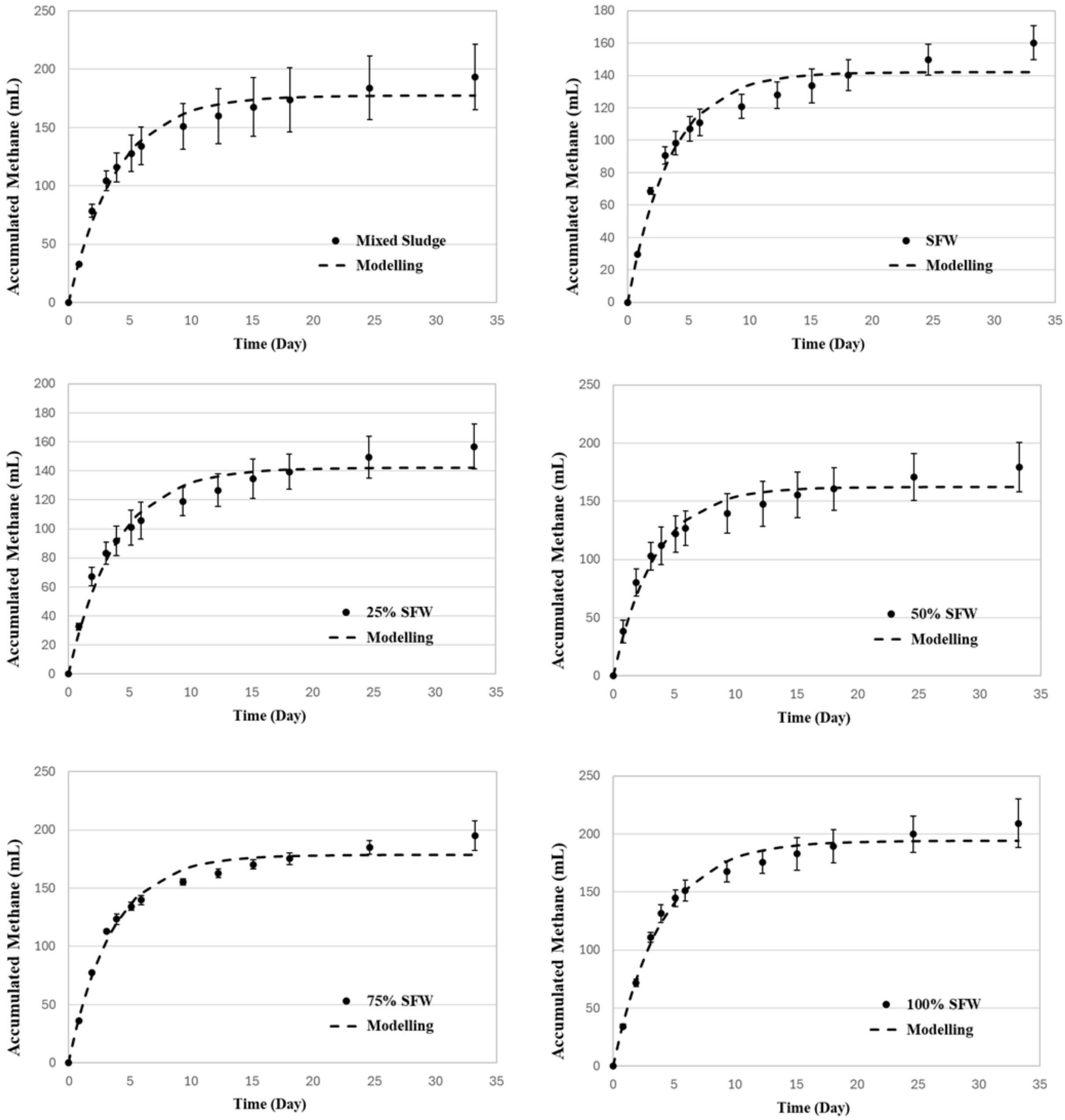


Figure 18 Cumulative methane production from BMP tests investigating co-digestion of SFW at a Municipal WWTP

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

APPENDIX B – Methane Production Curves from Co-digestion of GT at a WWTP

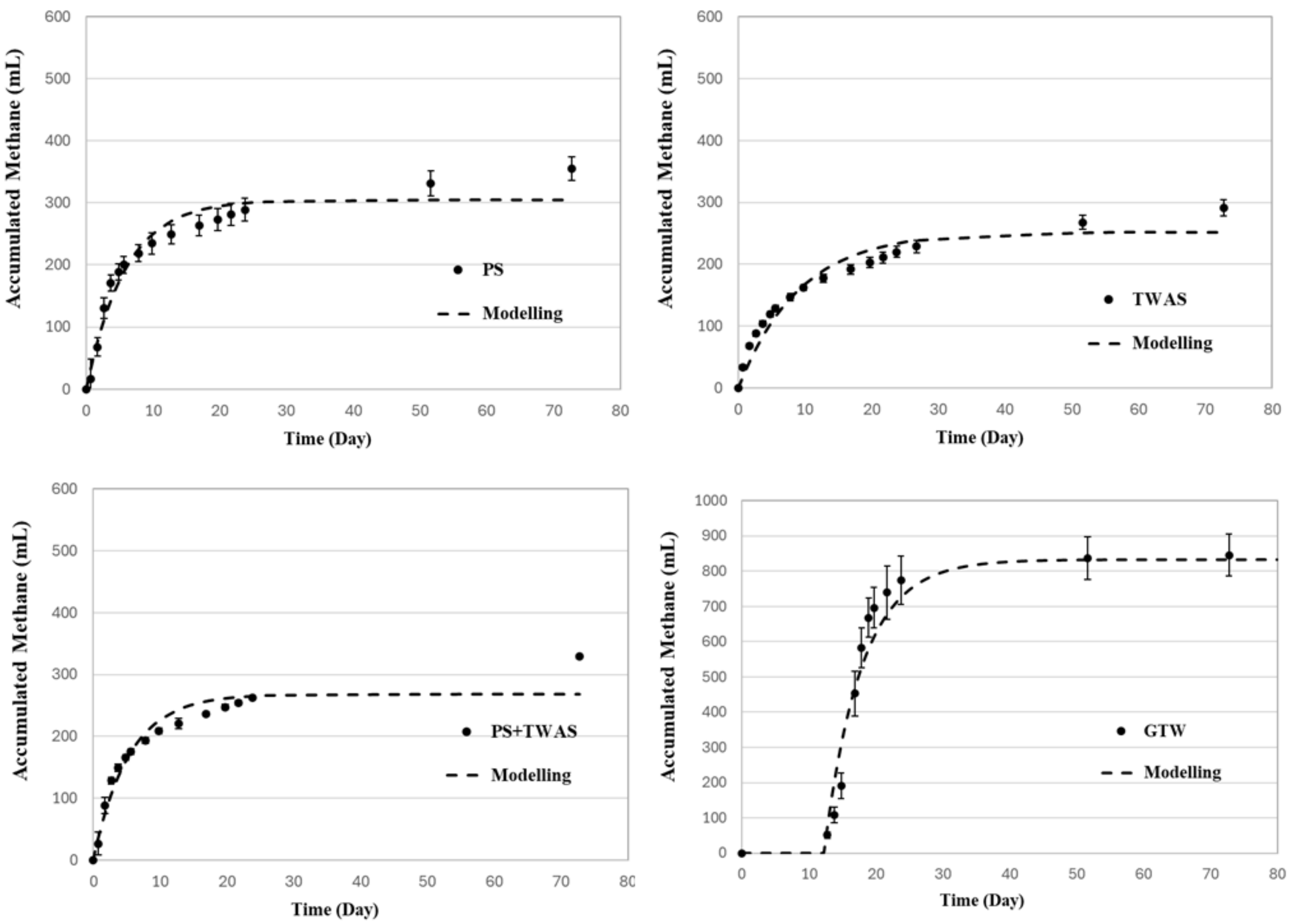


Figure 19 Cumulative methane production from mono-digestion controls used to assess co-digestion of GTW at a municipal WWTP

endfoodwaste.com.au
enquiries@endfoodwaste.com.au

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

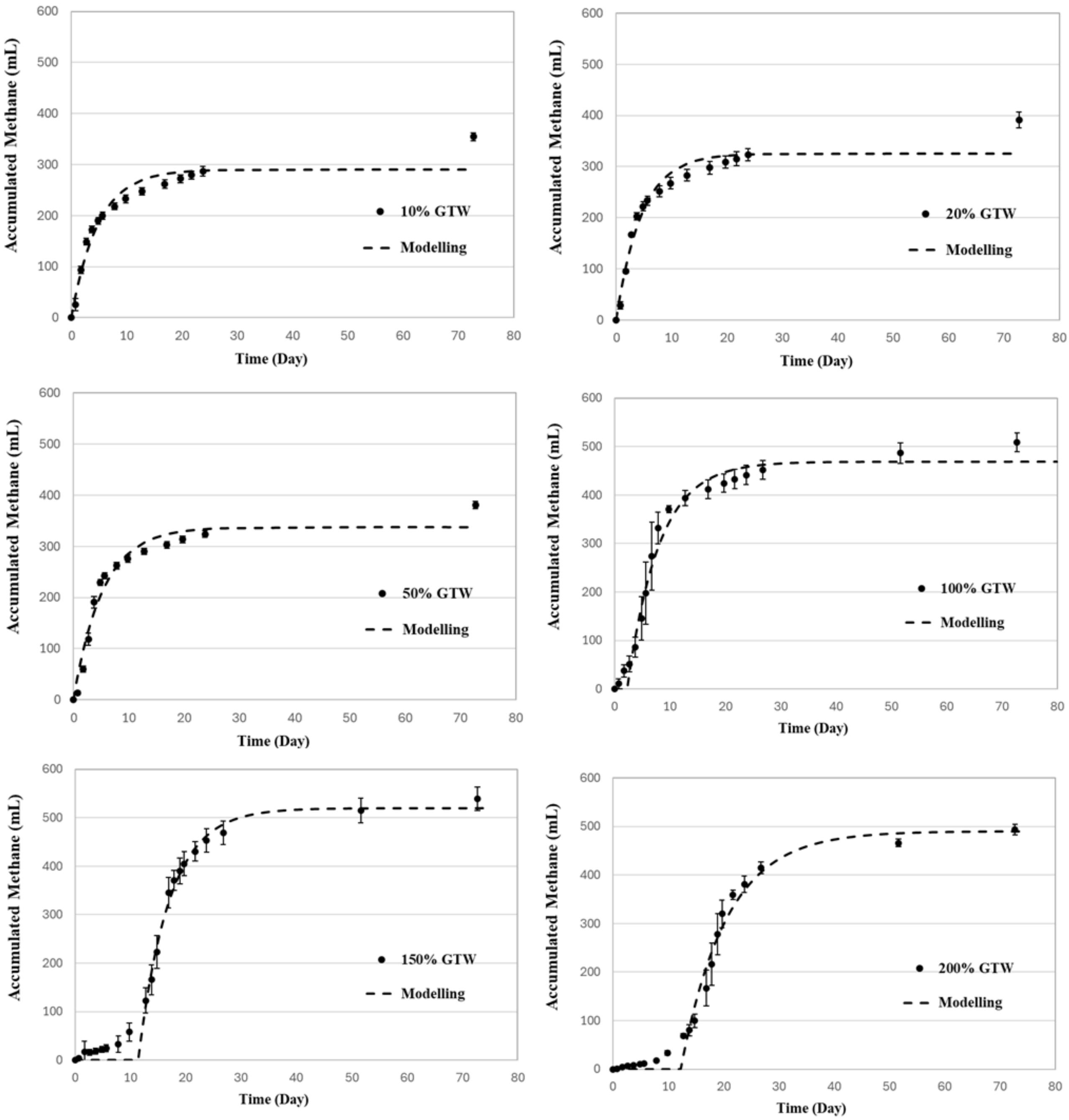


Figure 20 Cumulative methane production from BMP tests investigating co-digestion of GTW at a Municipal WWTP

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

APPENDIX C – Methane Production Curves from Co-digestion of GTW and DMP at a WWTP

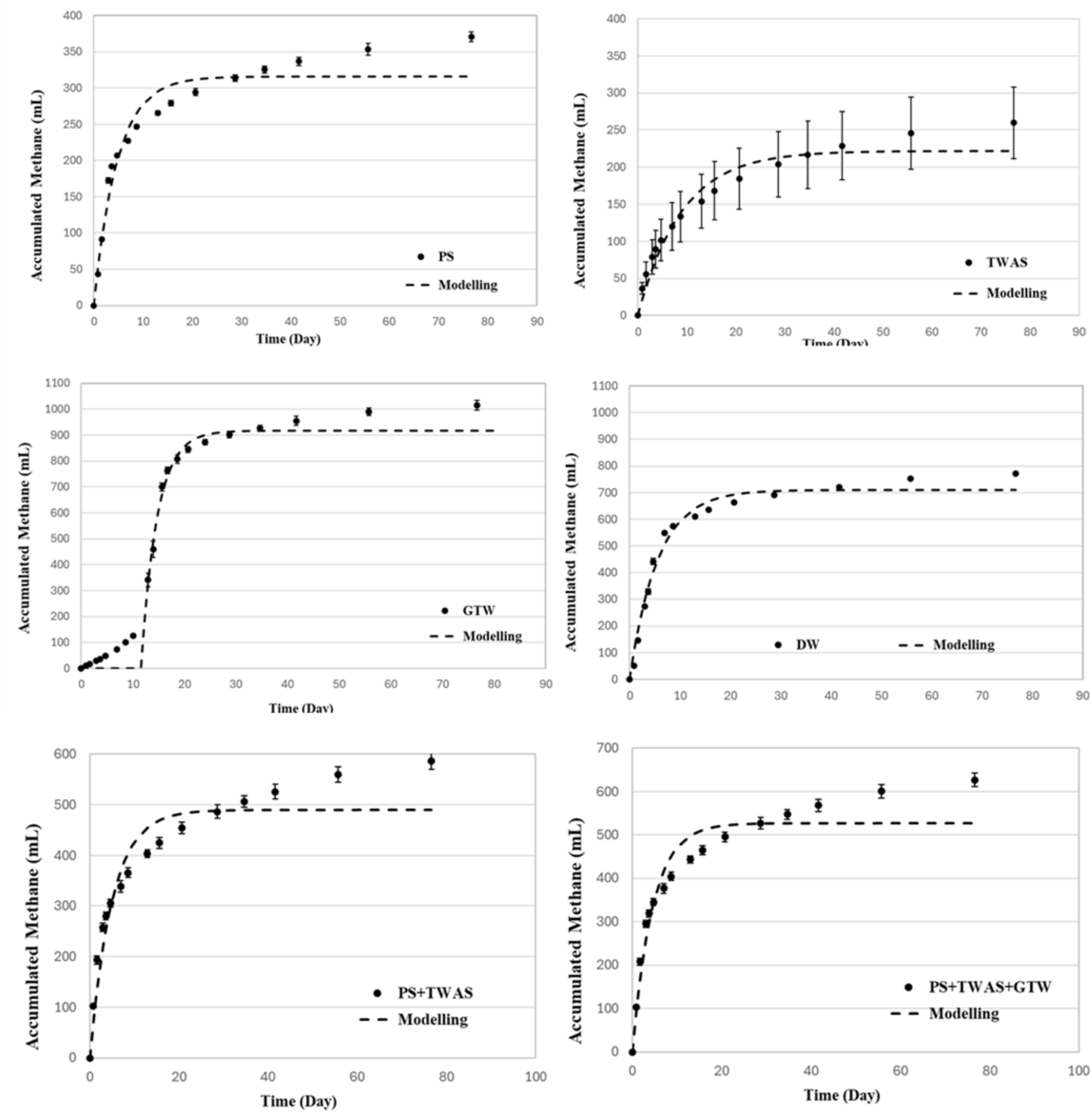


Figure 21 Cumulative methane production from mono-digestion controls used to assess co-digestion of DMP waste at a municipal WWTP treating a mixture of sewage sludge and GTW

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

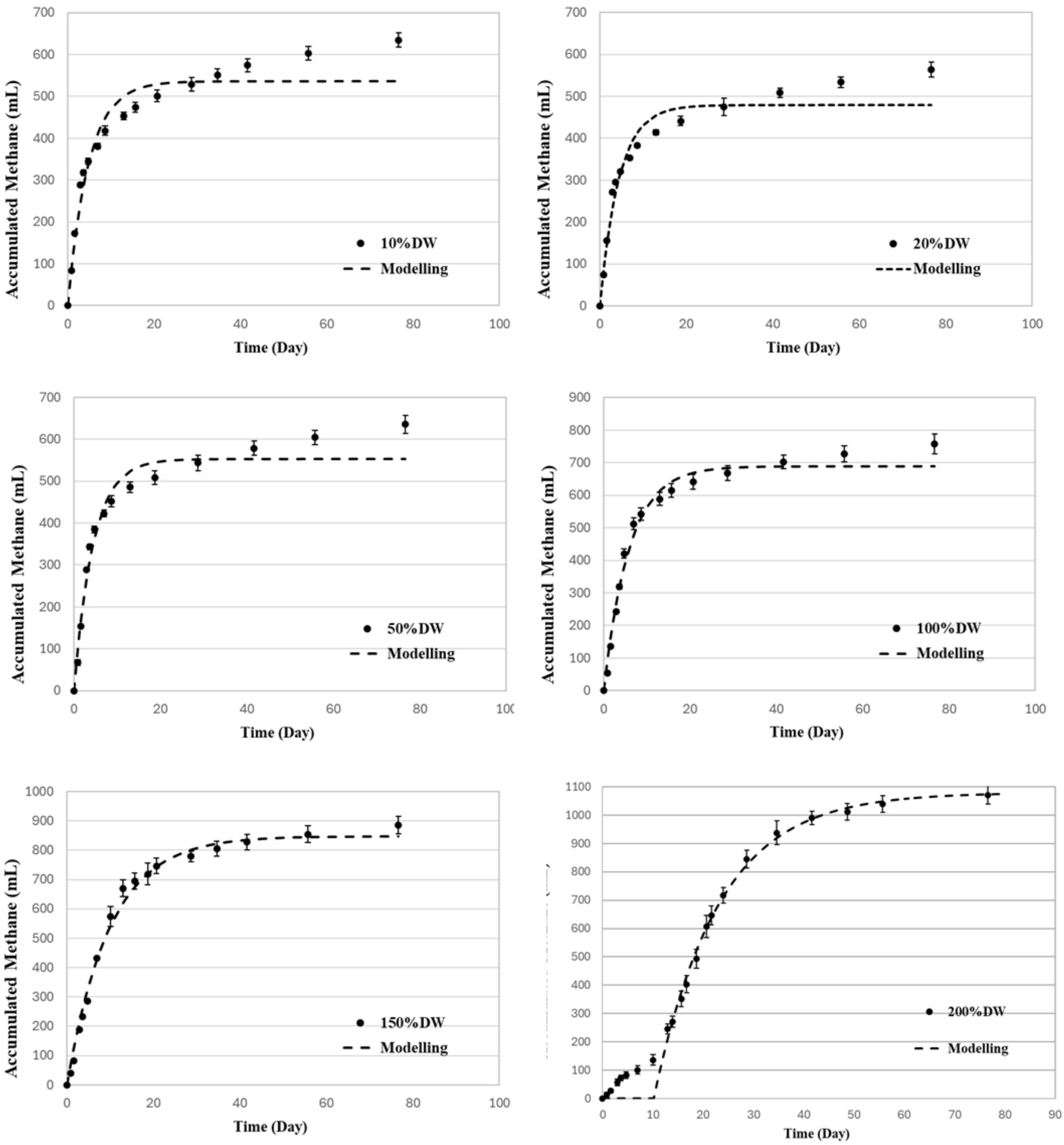


Figure 22 Cumulative methane production from BMP tests investigating co-digestion of DMP waste at a Municipal WWTP treating a mixture of sewage sludge and GTW

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

For further information please contact:

enquiries@endfoodwaste.com.au
or visit endfoodwaste.com.au

Australian Government
Department of Industry, Science and Resources
Cooperative Research Centres Program