Journal of Environmental Protection, 2025, 16(2), 148-179
https://www.scirp.org/journal/jep
ISSN Online: 2152-2219
ISSN Print: 2152-2197

Assessing the Effects of Anaerobic Co-Digestion with FOG and Food Waste Residuals on Biogas Production

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How to cite this paper: Sharmin, S., Meeroff, D.E., Ferdinand, L., Bloetscher, F. and Lashaki, M.J. (2025) Assessing the Effects of Anaerobic Co-Digestion with FOG and Food Waste Residuals on Biogas Production. *Journal of Environmental Protection*, **16**, 148-179.
https://doi.org/10.4236/jep.2025.162008

Received: January 23, 2025
Accepted: February 25, 2025
Published: February 28, 2025

Abstract

As global populations grow, the generation of various waste materials like fats, oils, and grease (FOG), fruit waste, and other perishable wastes increases concurrently. Disposal of these highly putrescible waste products in landfills consumes valuable landfill space. Anaerobic digestion can transform these waste materials into valuable components, including fertilizer and biogas, reducing the demand for landfill space. The current study is based on the hypothesis that incorporating high-strength organic waste into conventional wastewater sludge can enhance the production of onsite biogas at wastewater treatment plants, therefore contributing to the reduction of the plant's energy demands from the grid. The batch anaerobic biodegradability test assays were performed for 63 days to observe the impact on the biomethane yield from adding high-strength organic waste to the wastewater sludge and to investigate the combined effects of co-digesting two different preselected high-strength organic waste streams. Additionally, physicochemical characterization was performed on different fruit waste juicing residuals to indicate which fruit wastes might increase anaerobic digestion efficiency. The highest methane yield of 243 mL/gVS and 280 mL/gVS, respectively, were obtained with two mixtures having 10% FOG as the sole substrate and 10% FOG along with 10% fruit waste. The study also assessed the siloxane concentrations present as trace contaminants in the biogas samples. An initial economic feasibility assessment of food waste co-digestion at two wastewater treatment plants in Florida was conducted using the Co-Digestion Economic Analysis Tool (CoEAT) model. Based on the laboratory results, the analysis indicated a net positive benefit of \$39,472 for a medium-sized plant (10 - 30 MGD capacity) and \$52,488 for a larger plant (>30 MGD capacity) after 15 years, while diverting 10 - 18 tons/day of food waste from landfills with an anticipated minimal increase in sludge volume production at food waste additions less than 10% of the digester feed as stated in the literature.

Keywords

High-Strength Organic Waste, Fats, Oils, and Grease, Co-Digestion Economic Analysis Tool

1. Introduction

Nearly one-third of global food production is wasted at an annual cost of $990 billion [1]. In developed nations, up to 40% of this food waste is discarded at the post-consumer level [2]. Americans waste $408 billion of food, which costs an average family of four $1800 per year [3]. According to USEPA (2018) [4], the United States produces about 292.4 million tons of municipal solid waste (MSW) annually. The same USEPA (2018) study found that food waste constitutes 21.6% of the MSW waste stream. On the pre-consumer side, 43% of food waste from the food manufacturing and processing sector was anaerobically treated [5]. However, only 1% of the food waste produced by the food retail, food service, and residential sectors was managed by anaerobic digestion in 2019. Since the retail and service sector generates over 100 million tons of food waste per year, there is a potentially large amount material that could be diverted from landfills for energy capture via anaerobic co-digestion. With seven states in the U.S. potentially running out of landfill space within the next decade, finding alternative solutions for food waste disposal is essential. Converting food waste into anaerobic co-digestion feedstock offers dual benefits: it not only extends landfill lifespan but also generates biogas, a valuable renewable energy source [6].

Landfill disposal of food waste exacerbates environmental challenges due to the rapid biodegradation of organic matter in landfills. In 2020, the U.S. Environmental Protection Agency (USEPA) reported that municipal solid waste landfills released 94.2 million metric tons of carbon dioxide equivalents of methane, accounting for 15% of the nation's total methane emissions. Notably, 61% of fugitive methane emissions from food waste in landfills are released into the atmosphere rather than captured [5]. Given that methane is 28 times more effective than carbon dioxide at trapping atmospheric heat [7], these emissions significantly contribute to global greenhouse gas levels and climate change.

To address this issue, anaerobic co-digestion has emerged as a viable and well-established technology. This process converts organic waste into two valuable products: methane-rich biogas and a nutrient-rich solid byproduct. The biogas can be captured for electricity generation [8], while the solid byproduct serves as an effective fertilizer or soil amendment. The process takes place in a reactor vessel, where a consortium of anaerobic microorganisms breaks down high-strength organic matter—such as carbohydrates, proteins, and lipids—into simpler monomers. By diverting waste from landfills and transforming it into renewable energy and soil enhancers, anaerobic co-digestion mitigates the environmental impact of food waste, reduces landfill space demand, and decreases dependence on fossil fuels.

Anaerobic co-digestion is a process in which high-strength organic wastes such as Fats, Oils, and Grease (FOG) and/or food scraps are added to conventional anaerobic digesters to increase biogas production. These high-strength organic wastes contain high concentrations of readily biodegradable, carbon-rich compounds, often indicated by elevated chemical oxygen demand (COD) and volatile solids to total solids ratio (VS/TS) [9]. For example, FOG and food waste are characterized by a VS/TS ratio above 0.8 and COD values greater than 4500 mg/L as O_2 [10]-[14], indicating conditions favorable for biogas production. In contrast, low-strength municipal wastewater typically has a COD below 800 mg/L as O_2 and a lower VS/TS ratio [15].

While a higher VS/TS ratio (>0.8) in FOG and food waste suggests ample organic matter, it does not necessarily imply a higher proportion of biodegradable organic matter. Nonetheless, it has been reported that FOG and food waste can enhance the methane yield as they contain three times the methane production potential of biosolids or manure [16]. Furthermore, many wastewater treatment plants have spare capacity in their existing anaerobic digesters, enabling them to take extra organic wastes for co-digestion [17].

Anaerobic co-digestion offers multiple benefits, such as higher methane production potential, economic feasibility, and fewer upsets due to process instability from nutrient imbalances, pH changes, or toxic inhibitors. To increase methane production by co-digestion, substrates that are compatible and mixed in the proper ratios to avoid any system imbalance should be identified [18]. Co-digestion also results in greater volatile solids destruction with a corresponding marginal increase in biosolids production [19]. Co-digestion feedstocks may require pretreatment such as removal of undigestible contaminants like grit or plastic contamination, reduction in the particle size of substrates, mixing for homogenized slurry formation, and/or heating for flowability control. However, any increased costs incurred for preprocessing may be offset by enhanced biogas production or gate fees collected by the wastewater treatment facilities for managing food waste [20].

Anaerobic digesters typically operate under mesophilic (25˚C - 45˚C) or thermophilic (45˚C - 65˚C) conditions, influencing methanogenic growth rates, gas transfer, and sludge settling. Thermophilic digestion enhances methane production at lower hydraulic retention times but is less stable, while mesophilic conditions offer greater stability with longer retention times and lower yields [21] [22]. Methanogenic bacteria thrive within a pH range of 6.6 - 7.6 [23], but excessive volatile acid accumulation during acidogenesis can drop pH below 6, causing process inhibition [24]. Maintaining alkalinity between 1500 - 5000 mg/L as $CaCO_3$ with a volatile acid/alkalinity ratio of 0.10 - 0.35 is essential for stability [25].

Carbon and nitrogen are both essential for microbial cell growth. If the C:N ratio in the feedstock is too high, then there may not be enough nitrogen to support cell growth or the formation of amino acids, proteins, and nucleic acids, which can result in reduced biogas production. If the C:N ratio is too low, there may not be enough carbon to provide sufficient energy to support bacterial growth. Moreover, ammonia, resulting from the deamination of nitrogen-rich feedstocks, should be kept below 3000 mg/L as NH_3-N, as higher concentrations can be toxic to methanogens [26]. Therefore, it is desirable to have C:N ratio of 20:1 to 30:1 [27].

1.1. Related Works

1.1.1. FOG as a Feedstock for Anaerobic Digestion

Anaerobic co-digestion can be accomplished with a wide range of feedstocks such as food waste and high strength industrial byproducts added to sewage sludge solids [28]. However, the amount and quality of the biogas are influenced by both the feedstock composition and the operational conditions inside the digester [29]. Among the common high-strength organic waste feedstocks, FOG (fats, oils, and grease) and fruit waste juicing residuals are particularly prominent. FOG is one of the most lipid-rich materials [30] (refer to **Table S1** (supporting information)) sourced from grease traps, food processing operations, and food-based industries [31]. Improper handling of FOG can obstruct sewer lines and is responsible for 50% - 75% of the sanitary sewer overflows as it forms hardened deposits on the pipe walls, reducing the conveyance capacity, or even completely blocking the flow [32]. The cost of removing FOG deposits from the sewer lines can reach up to $25 billion in the United States annually [33] [34]. Given these challenges, anaerobic co-digestion of FOG with conventional wastewater sludge can be an effective technique in converting a costly waste problem into a valuable feedstock for biogas production [35].

The anaerobic digestion process occurs in four main stages: 1) hydrolysis, 2) acidogenesis, 3) acetogenesis, and 4) methanogenesis. The composition of the feedstock plays a vital role in maintaining stability at each stage of the digestion process. For instance, during anaerobic co-digestion, hydrolysis of FOG produces long-chain fatty acids (LCFAs) such as oleate and palmitate [36] that may lower the pH and inhibit methanogenesis [32]. LCFAs are insoluble, tend to coagulate, and are typically less bioavailable, which can limit methane generation. Therefore, the decomposition of lipids can be the rate-limiting step in anaerobic co-digestion [33]. When FOG loading rates are optimized, methane production from anaerobic co-digestion of FOG can increase by 140% - 620% compared to the methane production from digestion of wastewater sludge alone [37]. However, beyond a certain loading threshold, the inhibitory effects of high solids content and LCFA accumulation can disrupt the digestion process [11], underscoring the delicate balance required for efficient co-digestion.

EI Mashad and Zhang (2020) [38] conducted batch scale anaerobic co-digestion under mesophilic conditions for 25 days with an organic loading of 4 g/L for different feedstocks. The methane yield results are shown in **Figure 1**. The highest methane yield was obtained from grease trap waste (FOG), while fish waste might have exhibited a higher methane yield than fruit waste and mixed food waste due to the presence of fish oils.

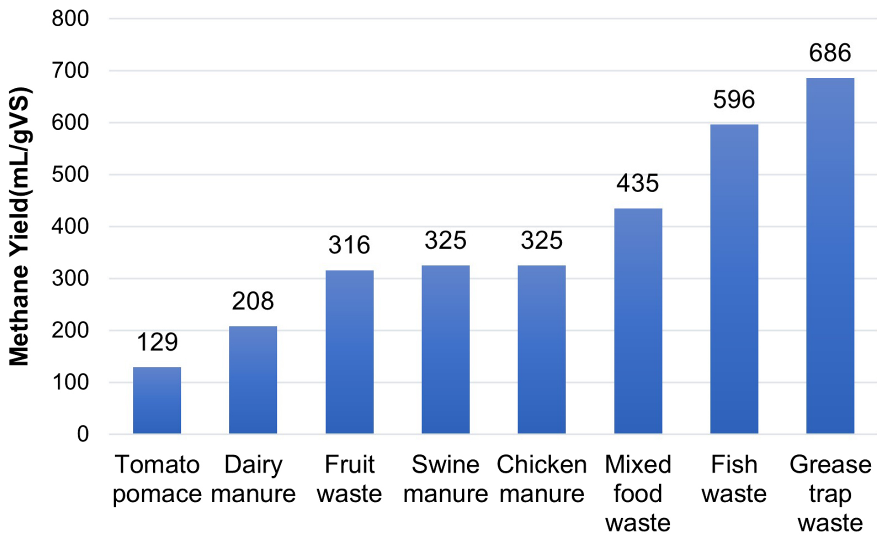


Figure 1. Energy production from different organic waste feedstocks (EI Mashad and Zhang, 2020, adapted from Libre Texts Engineering having Creative Commons license).

Collin *et al.* (2020) [39] compared the methane potential of different FOG substrates in 60-day batch tests under mesophilic conditions. Samples collected further from their source exhibited more variation due to dilution and the presence of contaminants. FOG from floating scum had the lowest lipid content and lowest methane potential, suggesting that its energy per unit mass was diluted by mixing with wastewater. In this study, FOG was collected from floating scum. This material was readily available from the centralized wastewater treatment facility and represents the most conservative feedstock from a methane yield perspective.

The effectiveness of FOG digestion depends not only on its type but also on the substrate-to-inoculum (S/I) ratio, which governs the quantity and quality of biogas produced during anaerobic co-digestion. Mahat *et al.* (2020) [36] performed batch experiments on food processing wastewater (FPW) with FOG feedstock and anaerobic digestate as the inoculum under mesophilic conditions with a solids retention time (SRT) of 54 days. The maximum biogas yield of 229 mL/gVS was achieved with a methane production yield of 201 mL/gVS when the ratio of FPW to anaerobic digestate was 1:1 on a volume-per-volume basis in reactors with a working volume of 100 mL. The methane yield decreased to 67.5 mL/gVS when the ratio was 2:1. Increasing the FPW ratio raised the lipid loading into the system, which, in turn, increased the LCFAs concentration inside the digesters. The lower amount of anaerobes at a 2:1 ratio may have contributed to incomplete grease degradation. Additionally, the inhibitory effects of LCFAs—including cell damage, reduced cell permeability, and adsorption onto microbial cell walls that limits nutrient transport—further impacted biogas production [36] [40]. Nonetheless, it has been reported that adding FOG at a rate of 10-30% of the total digester feed to two full-scale wastewater anaerobic digesters increased biogas production by 30% - 80% [41].

1.1.2. Fruit Waste as a Feedstock for Anaerobic Digestion

Apart from the controlled addition of FOG, incorporating a complementary feedstock such as fruit waste juicing residuals could enhance the buffering capacity and improve overall digestion stability. Fruit waste residuals are a carbohydrate-rich feedstock that might help alleviate the inhibitory effects of FOG during anaerobic co-digestion. Fruits provide essential nutrients, and exponential population growth has driven an increased demand for fruits and processed fruit products. In 2020, the global production of bananas was 120 million metric tons followed by watermelons (102 MMT), apples (86 MMT), grapes (78 MMT), and oranges (75 MMT) [42]. With respect to apples, the United States accounts for 6.2% of the total worldwide production. However, only 70% - 75% of the total apples produced are consumed directly, while the remaining fraction is used to make various processed products, 65% of which are used to manufacture juice [43]. The remaining byproducts, comprising fruit pulp, stems, peels, and cores, are collected as fruit waste residuals characterized by a high moisture content (>70%) and high sugar content (~75%), enhancing biodegradability and methane formation [44]. These large amounts of fruit waste residuals in the municipal solid waste stream not only places stress on the land availability for disposal but their high moisture content (>70%) results in low heating value 5815 KJ/kg (<2500 BTU/lb) compared to MSW without organic waste 11630 KJ/kg (~5000 BTU/lb) [45], making this material less suitable for incineration.

Anaerobic co-digestion with energy recovery for feedstocks with fruit waste residuals can be a viable option for efficient management of these wastes as they contain readily hydrolysable soluble sugars, organic acids, and a desirable C:N ratio between 20 and 30:1 [46]. However, utilizing fruit waste residuals as a sole substrate can result in the rapid conversion of carbohydrate polymers into volatile fatty acids (VFAs), which can lower the pH, resulting in the potential souring of the digester requiring alkalinity adjustment [44] [47].

In previous research, Hallaji *et al.* (2019) [48] carried out anaerobic co-digestion using 1000 mL bioreactors under mesophilic conditions for a period of 30 days. The feedstocks consisted of anaerobic digestate, waste activated sludge, cheese whey, and fruit waste. The maximum methane yield of 384 mL/gVS occurred when 15% combined cheese whey and fruit waste were mixed with 85% anaerobic digestate/waste activated sludge to achieve a 1.2 substrate-to-inoculum ratio. The fruit waste was a blended slurry of equal parts by weight of apple, tomato, carrot, orange, and potato. Since few studies have determined the methane potential of fruit waste residuals, its potential as a suitable co-digestion feedstock still needs to be more fully investigated.

1.2. Evaluation of Siloxane Levels in Biogas

Besides assessing the methane yield from various feedstocks, it is also imperative to evaluate the quality of biogas to ensure its usability in downstream applications. In addition to carbon dioxide, biogas from anaerobic co-digestion may have trace impurities, such as siloxanes, hydrogen sulfide, NO_x, volatile organic compounds, and ammonia that affect biogas quality and its use as a renewable energy source [49]. Siloxanes are volatile silicon-based compounds from personal care products, fuel additives, and anti-foaming agents that can contaminate biogas. Siloxanes are abrasive and cause excess wear on engine parts, turbines, boilers, and heating elements. Siloxanes occur in two types: 1) polydimethylsiloxanes (PDMS), which have higher molecular weight and low vapor pressure and 2) volatile methyl siloxanes (VMS), which have lower molecular weight and are highly volatile. In raw wastewater, some VMS and most PDMS adsorb onto sludge solids because they are hydrophobic and then enter the anaerobic digester. After digestion, biogas will contain VMS from direct volatilization of solid-bound VMS alongside hydrolysis of PDMS. During biogas combustion, siloxanes decompose into silicon and oxygen, forming hard deposits that can build up and damage combustion equipment, reducing useful life and increasing maintenance costs. Therefore, VMS may need to be removed from biogas before energy recovery operations [50].

1.3. Objective of the Research Work

The primary objective of this study was to conduct biochemical methane potential tests under mesophilic conditions using high-strength organic waste feedstocks containing FOG and fruit waste juicing residuals. Co-digestion was achieved by mixing the specified substrates with wastewater treatment plant sludge and inoculum in suitable ratios, while the performance of the different combinations were evaluated based on measured biogas/methane production rates and key water quality parameters. Moreover, the concentration of siloxanes in biogas samples was measured to assess the feasibility of utilizing the anaerobic co-digestion generated biogas in energy recovery applications. The study intends to provide data to determine if additional siloxane removal systems will be needed if anaerobic co-digestion of FOG and fruit juicing waste residuals were adopted at full scale. The study also assessed the preliminary economic viability of implementing food waste diversion programs and co-digestion processes in bioenergy generation using the Co-Digestion Economic Assessment Tool (CoEAT) model with inputs developed from this work.

2. Materials and Methodology

For the batch lab scale anaerobic co-digestion experiments, anaerobically digested sewage sludge was used as the inoculum, collected from the primary anaerobic digester from a local conventional anaerobic digestion operation at a publicly owned wastewater treatment plant. Fats, oils, and grease (FOG) were collected from the surface of the primary clarifier, and thickened waste activated sludge (TWAS) was collected from the bottom hopper of the secondary clarifier. These feedstocks were obtained from a medium-sized wastewater treatment facility (10 - 30 MGD capacity) (Boca Raton Glades Road Wastewater Treatment Plant). Even though FOG collected as floating scum has lower methane potential compared to FOG sourced directly from food service establishments, the ease of accessibility was a main consideration. This approach underscores the practicality of implementing anaerobic digestion by utilizing waste materials that are readily available and easier to source locally. Different fruit juicing waste residuals were obtained from a local small processing facility (Raw Juce Company) to characterize the fruit juicing waste residuals and select suitable candidate food waste feedstocks to undergo anaerobic co-digestion treatment. Prior to analysis, the samples were refrigerated.

2.1. Physico-Chemical Characteristics

Key water quality parameters were analyzed prior to incubation and periodically throughout the batch anaerobic co-digestion experiments. These included pH, alkalinity (mg/L as $CaCO_3$), total volatile acids (mg/L as CH_3COOH), ammonia (mg/L as NH_3-N), chemical oxygen demand (COD; mg/L as O_2), total nitrogen (TN; mg/L as N), total solids (% wet weight), and volatile solids (% total solids). The water quality parameters were measured following the Standard Methods for the Examination of Water and Wastewater [51].

Fruit waste characterization was performed to identify the most suitable fruit juicing waste residuals to be used as a substrate feedstock for anaerobic co-digestion. Waste products from the processing of green apples, lemons, pears, red apples, cucumbers, and kale were collected from Raw Juce Company in sterile Whirl-pak bags. About 30 grams of each material was measured and then combined with 100 mL of distilled water in a commercial blender to form a homogeneous slurry that was subsequently analyzed for each of the water quality parameters of interest. Initial characterization was also performed on the individual feedstock of anaerobically co-digested sewage sludge, thickened waste activated sludge (TWAS), and FOG. The C:N ratio of the feedstocks was calculated by converting the chemical oxygen demand (COD), expressed in mg/L as O_2, to mg/L as C, and then dividing this value by the total nitrogen (TN), expressed in mg/L as N.

2.2. Experimental Procedure

To determine the biodegradability and technical feasibility of a range of substrates and feedstocks for anaerobic digestion, batch anaerobic co-digestion bioassay tests were conducted in 500 mL serum bottles. Specific substrates were selected based on factors discussed in the introduction. Tests were conducted at mesophilic temperatures (35˚C ± 0.5˚C) for SRT = 63 days and at adequate ratios of substrate to inoculum on a volume basis, as shown in **Table 1**. The substrate ratios for this study were selected based on guidance from the USEPA Quality Assurance Protocol Plan (QAPP) and findings from prior research. Two controls—100% anaerobic digestate and 100% TWAS—were included for comparison purposes.

Anaerobic digestate and TWAS was mixed with only one type of substrate at a time, followed by a combination of both substrates. This approach provided valuable insights into the effects of each individual substrate and in combination on biogas production. The feedstock combination ratios were selected primarily based on previous research indicating that adding FOG at a rate of 10% - 30% of the total digester feed to two full-scale wastewater anaerobic digesters increased biogas production by 30% - 80% [41] [52]. Furthermore, a 50% inoculum ratio was maintained across all mixtures within the working volume for simulating a realistic scenario where a full-scale anaerobic digester at a wastewater treatment plant typically operates at 50% - 80% capacity. At this inoculum level, adequate microbial biomass will be present to degrade the substrates while maintaining a headspace of 400 mL in all the 500 mL serum bottles for safe and efficient biogas collection.

Table 1. List of specific mixtures tested.

Sample Type	Ratio	Volume (mL)				
		Inoculum	TWAS	FOG	HSW	Total
Control Blank	100S[a]	100	0	0	0	100
TWAS Only	100TWAS[b]	0	100	0	0	100
TWAS/FOG	50S:40TWAS:10FOG[c]	50	40	10	0	100
TWAS/HSW[d]	50S:40TWAS:10RA[e]	50	40	0	10	100
TWAS/FOG/HSW	50S:30TWAS:10FOG:10RA	50	30	10	10	100

[a]S: anaerobic digestate; [b]TWAS: thickened waste activated sludge; [c]FOG: fats, oils, and grease; [d]HSW: high-strength waste; [e]RA: red apple juicing waste residuals.

Mixtures were prepared in duplicate in 300 mL beakers and then transferred to a 500 mL serum bottle with a working volume of 100 mL and headspace of 400 mL. Therefore, two serum bottles were used for each ratio for reproducibility of the results in the batch bioassay tests. Prior to incubation, alkalinity, pH, and volatile acids of all the mixtures were measured. The volatile acids/alkalinity ratio of all mixtures was found to be greater than 0.3. Therefore, approximately 2 grams of sodium bicarbonate powder were added in all mixtures before incubation, and the ratio of volatile acids/alkalinity was brought to within 0.1 - 0.3. Subsequently, N_2 gas was used to purge the headspace of each serum bottle for at least 1 minute to create anaerobic conditions. After purging, an aluminum cap with rubber septum was immediately secured over the serum bottle using a specialized crimping tool. Serum bottles were then partly submerged in a water bath and incubated at 35˚C ± 0.5˚C (**Figure S1(a)** (supporting information)). Bottles were manually inverted ten times per day during the incubation period to ensure adequate contact between microorganisms and the substrate, facilitate uniform distribution of temperature, and prevent scum formation, solids deposition, and accumulation of toxic compounds.

Biogas sample duplicates were collected periodically using an 18-gauge, 1.5-inch needle attached to a 550 mL plastic syringe (**Figure S1(b)** (supporting information)). The 550 mL capacity plastic syringe was selected with respect to the 500 mL capacity serum bottle to accommodate for the full biogas volume expected to be produced in each measurement interval minimizing the need for repeated withdrawals of the biogas from the headspace of each serum bottle. The syringe was tightly fitted to a 2 micron syringe filter via an adapter to trap any water vapor in the biogas to ensure accuracy in biogas volume and composition measurements. The filter assembly was then connected to the needle. Afterwards, the needle was used to pierce through the rubber septum and the plunger was allowed to move freely until the internal pressure was neutralized and the plunger stopped moving, indicating that equilibrium was reached. The volume of biogas collected was then recorded from the graduated marks of the syringe. Syringe collection of biogas is flexible, economical, convenient and easy to set up with minimal biogas loss. Biogas samples were then injected into a portable biogas analyzer (LandGEM 5000+), and the biogas composition in percent by volume (CH_4, CO_2, and O_2) was recorded. The instrument was purged with ambient air and then calibrated daily using specialty calibration gas with composition of 50% CH_4, 35% CO_2, and 15% N_2.

2.3. Siloxane Measurement

Siloxanes were analyzed by a certified laboratory (Atmospheric Analysis & Consulting, Inc.) using GC/MS in accordance with EPA Method TO-15M, which defines the performance criteria of sampling and analysis of volatile compounds in air contained in sample canisters. Once per run, biogas samples were withdrawn from the digesters as described in Section 2.2 and then transferred to sample collection canisters via suction using tubing connected to a filter to trap any water vapor present and reduce interference from any trace constituents.

2.4. CoEAT Model

The co-digestion economic analysis tool (CoEAT) is an Excel-based framework designed by USEPA (2010) to assess the preliminary economic feasibility of proposed anaerobic co-digestion. The CoEAT model calculates fixed and recurring costs, solid waste diversion savings, capital investment, and expected biogas production and energy value [53] based on user-provided input. The model considers feedstock availability, capital investment, food waste collection capacity, transportation distances, number of personnel required, average labor cost in the service area, and feedstock moisture content. Additionally, the model accounts for digester sizing, solids retention times, digester capital costs, operation and maintenance requirements, and financial data.

In this research study, the CoEAT model was run for two scenarios: 1) a medium-sized wastewater treatment plant (10 - 30 MGD capacity) receiving 10 tons/day of supplemental food waste but without co-generation capability and 2) a larger-sized wastewater treatment plant (>30 MGD capacity) receiving 20 tons/day of supplemental food waste with an existing co-generation plant. Additionally, the cost of co-digestion on a per ton basis was determined manually by considering the total capital cost, total operating cost, revenue earned from replacing grid-supplied electricity with biogas electricity generation and avoided landfill tipping fees, as well as revenue earned from implementing a food collection fee in the service area. Table 2 shows the input parameters considered to perform the initial economic feasibility assessment using CoEAT model for both the medium-sized and larger-sized wastewater treatment plants.

Table 2. Input parameters provided to the CoEAT model for both medium-sized and larger-sized wastewater treatment plants

Input item	Input value for scenario 1	Input value for scenario 2
Number of digesters	3 primary (2 operational, 1 redundant), 1 secondary	2 primary (operating); 2 secondary (operating); 1 redundant
Custom feedstock audit	10 tons/day (5 tons/day per digester as specified by the plant)	20 tons/day (900 tons of food waste generated daily, 2% diverted = 20 tons/day
Percent of rejected food waste due to contamination	0.0	0.0
Diameter of the digester	80 feet	65 feet
Height of the digester	23 feet	34 feet
Average wastewater flow	14 MGD	21 MGD
Effective operating capacity	80%	
Biogas Production Rate	To be determined experimentally	
In the absence of co-digestion does your food waste goes to landfill	yes	
Capital cost of the feedstock collection trucks	$100,000 [54]	
How many tons does your typical food waste pickup truck hold	16 tons (80% of 20-ton truck)	
The landfill tipping fee in the service area	$42 (specific to the county)	
The tipping fee at the digester	$0	
The average number of miles for each roundtrip for each truck to complete a food waste pickup and delivery to the digester	88 miles	77 miles
The average number of miles for each roundtrip to dispose of the biosolids (landfilled or land applied)	70 miles	60 miles
Will digester biosolids waste be landfilled?	no	
Will digester biosolids waste be land applied?	yes	
Feedstock access costs in the service area	$0.0	

Continued

Feedstock pre-processing cost based on tons/day	$91 per ton per day	
Average labor cost in the service area	$31 per hour (service area-specific rates (e.g., supervisor, laborer, driver)	
Number of full-time personnel needed to support feedstock acquisition and digester operations	8 (6 at the plant (2 per shift), 1 at the transfer station, 1 driver)	
Consumer Price Index in the service area	1.1%	
Discount rate used for investments	3.0%	
Finance rate used for investments (for a period of 15 years)	5.0%	
Annual operation and maintenance cost of the digester	$120,000	$150,000
Organization's current electricity costs	$0.16 kWh	$0.12 kWh
Organization's current natural gas costs	$13.66 MMBtu (nationwide)	
Ancillary equipment costs	1,413,700 (default values)	

The average number of roundtrip miles per collection truck to complete a food waste pickup and delivery was determined using Equation (1). The average number of roundtrip miles to dispose of the biosolids (landfilled or land applied) was calculated using Equation (2), as follows.

$$D_{food} = \left(R_{food} + D_{plant\text{-}to\text{-}station}\right) \times 2 \tag{1}$$

$$D_{biosolid} = 2 \times D_{plant\text{-}to\text{-}biosolid} \tag{2}$$

D_{food} represents average roundtrip distance for collecting and transporting food waste to the digester (in miles), R_{food} represents the average radius of the service area, $D_{plant\text{-}to\text{-}station}$ denotes the distance between the wastewater treatment plant and the transfer station (in miles). $D_{biosolid}$ denotes the average roundtrip distance for biosolids disposal (in miles) and $D_{plant\text{-}to\text{-}biosolid}$ is the distance between the wastewater treatment plant and the biosolids processing or disposal site (in miles)

The food waste preprocessing costs at the digester location and transfer station were estimated to be $91 per ton per day [55], considering the costs associated with preprocessing, which includes receiving stations, pumps, heaters, odor control, piping, and grinders, etc. Lastly, default values were used for the ancillary equipment costs incorporated during the modeling scenarios.

3. Results and Discussion

3.1. Summary of Waste Characterization Parameters for Individual Feedstock

Table 3 summarizes the physical and chemical characteristics of each feedstock tested. The FOG and fruit juicing waste residuals were acidic with low to no alkalinity. The inoculum, thickened waste activated sludge, and FOG had low C:N ratios (20-30:1 is ideal for anaerobic co-digestion [27]). For efficient anaerobic co-digestion to occur, a substrate with a low C:N ratio, such as FOG, should be co-digested with a feedstock that has a high C:N ratio [46]. Red apple juicing waste residuals had the highest C:N ratio (135) among the high-strength organic waste feedstocks tested. Even though lemons had C:N ratio of 30, the presence of citrus acid and D-limonene, an antimicrobial agent present on the lemon peels are toxic to microbial cells during AD, resulting in catastrophic failure of the digester [56]. On the other hand, kale and cucumber had C:N ratios below 10 indicating unsuitability of these feedstocks as an AD additive. Therefore, selecting a mixture of fruit waste might have reduced the methane yield. The selection of abundant, locally available red apple waste as a sole fruit waste residual reduced the variability in the AD process, ensuring consistency and reproducibility in the methane yield results and the influence on pH and VFAs, such that the measured methane production rate can be attributed to red apple waste's specific characteristics. Besides, preliminary studies were conducted on red apple, pear, and lemon juicing waste residuals, which indicated that red apple waste had the highest methane production potential (523 mL/gVS) compared to pear waste (325 mL/gVS) and lemon waste (30 mL/gVS) [55]. Therefore, the selection of red apple waste for the batch bioassay tests was based on prior experimental evidence demonstrating superior performance and its distinctive properties (C:N ratio of 135).

Table 3. Characteristics of anaerobically digested sewage sludge (inoculum), TWAS, FOG, and different fruit waste juicing residuals.

Parameter	Inoculum	Thickened Waste Activated Sludge (TWAS)	High-Strength Organic Waste Feedstocks						
			FOG	Lemons	Kale	Cucumber	Green Apple	Pear	Red Apple
pH	7.79	7.78	5.47	3.10	5.33	5.45	4.09	3.96	4.40
Alkalinity (mg/L as $CaCO_3$)	16,700	10,400	1150	N/A	50	75	<50	<50	<50
Total Volatile Acids (mg/L as CH_3COOH)	2070	3324	1285	1958	1063	678	945	1163	1065
Ammonia (mg/L as NH_3-N)	210	34	17	70	25	19	60	61	16
Chemical Oxygen Demand (mg/L as O_2)	3000	3300	600	15,000	3000	1700	8300	12,000	7900
Total Nitrogen (mg/L as N)	420	2820	42	184	142	84	60	60	22
Total Solids (% wet weight)	1.90	4.70	0.20	1.43	0.92	1.47	1.95	1.33	1.36
Volatile Solids (% total solids)	74	77	96	97	99	95	99.6	96	97.5
C:N ratio	2.7	0.4	5.4	30	7.9	7.6	52	75	135

While we acknowledge that a mixed fruit waste approach could provide a broader spectrum of analysis and a more realistic scenario, our goal was to enhance methane yield while maintaining uniformity in substrate composition. Moreover, this study provides a comprehensive analysis of the behavior of red apple waste during anaerobic digestion, disseminating useful baseline data for future studies when mixed fruit waste will be employed as a comparative feedstock. Additionally, none of the feedstocks had toxic levels of ammonia (>3000 mg/L as NH_3-N; [26]).

3.2. Monitoring of Chemical Parameters and Stability of Batch Biomethane Potential Tests

3.2.1. Variation in Chemical Oxygen Demand (COD) Over the Incubation Period

Figure 2 shows the variation in COD levels of different mixtures over time. On day 7, the COD values of all mixtures increased, including controls attributed to hydrolysis and solubilization of particulate organics that increased the bioavailable organic content and stimulated microbial growth. The COD of the 100% inoculum fluctuated throughout the incubation period but tended towards stabilization. Beyond 42 days, the mixtures generally experienced a decline in the rate of organic consumption, indicating evidence of stabilization.

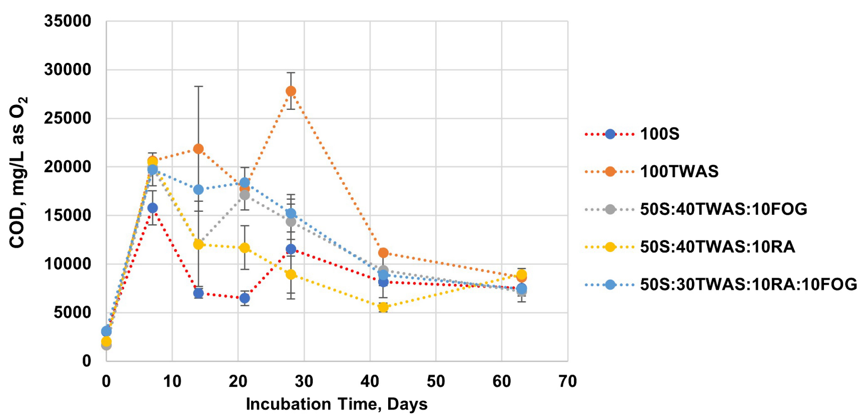


Figure 2. Variation in COD (mg/L as O_2) of the mixtures monitored over 63 days.

3.2.2. Variation in Ammonia Over the Incubation Period

Figure 3 shows the variation in ammonia over time. In general, ammonia concentration increased due to the hydrolysis of nitrogen-bound organic molecules, resulting in ammonia release. Proteins are large organic macromolecules created from building blocks of amino acids linked by peptide bonds. During the hydrolysis stage of anaerobic digestion, larger protein molecules are decomposed into polypeptides and simpler amino acids that undergo further degradation to form volatile fatty acids, carbon dioxide, hydrogen, and ammonia [36]. Nevertheless, throughout the incubation period, ammonia levels in the control and all other tested mixtures remained below the toxic threshold limit (~3000 mg/L as NH_3-N; [26]). A full-scale anaerobic digester typically operates with an SRT of 30 days, and Figure 3 suggests that the ammonia concentrations in all mixtures tested were well below the inhibitory level after an incubation period of 28 days. The observed increase in ammonia concentrations at SRT > 42 days could be attributed to cell lysis, releasing cellular proteins and nucleic acids that served as an additional nitrogen source similar to the phenomenon observed by Chuchat and Skolpap (2015) [57] during anaerobic digestion of waste activated sludge.

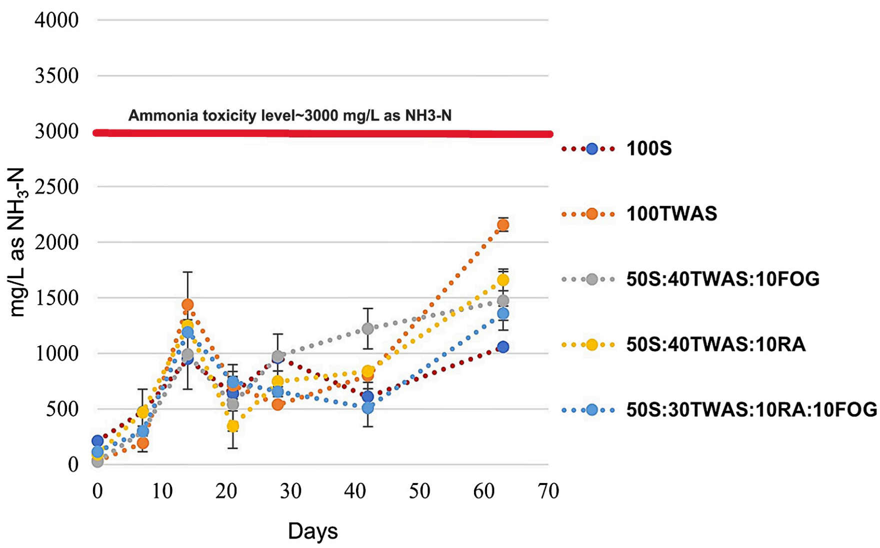


Figure 3. Variation in ammonia (mg/L as NH_3-N) of the mixtures over 63 days.

3.2.3. Variation in Total Nitrogen (TN) over the Incubation Period

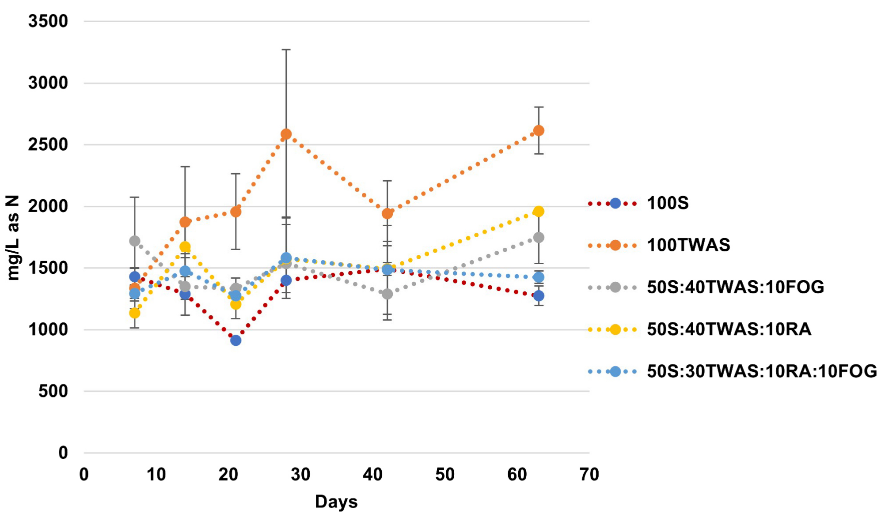


Figure 4. Variation in total nitrogen (mg/L as N) of the mixtures over 63 days.

Figure 4 shows the variation in total nitrogen measurements over the incubation period carried out on the slurry and includes the particulate organic matter. Unlike the carbon content that decreases after the digestion due to the conversion of organics into methane, the total nitrogen content remains relatively constant as the speciation may change. As expected, the total nitrogen content remained relatively stable across all mixtures and controls, with fluctuations observed specifically in the TWAS control. Figure 4 shows that the TWAS control had higher TN values compared to the feedstocks that contained high-strength organic wastes.

3.2.4. Variation in Alkalinity Over the Incubation Period

Figure 5 shows the variation in alkalinity over time. For mixtures with 10% FOG, alkalinity decreased until day 21. On day 7, the alkalinity fell below the minimum recommended alkalinity level (5000 mg/L as $CaCO_3$) inside the digester in one of the duplicate samples containing 10% FOG and 10% red apple juicing waste residuals. The decrease might be attributed to the rapid degradation of soluble organic sugars into volatile acids. However, the pH and alkalinity values of the mixture later recovered and remained stable, possibly because ammonia was released as digestion continued.

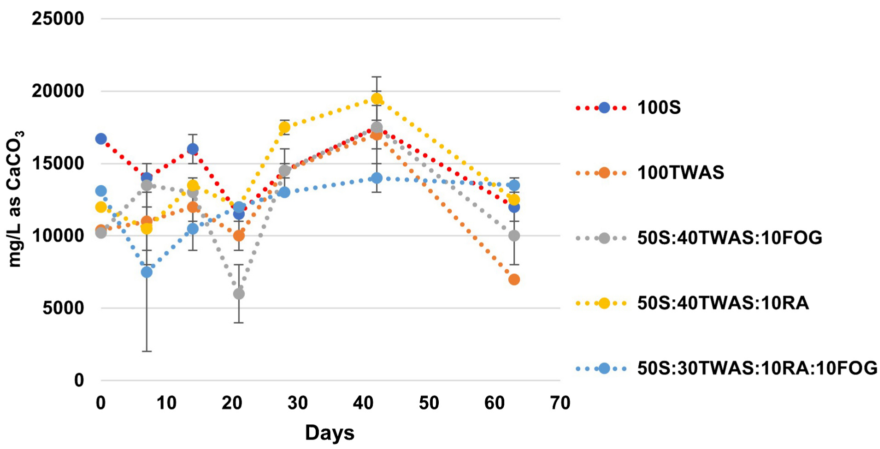


Figure 5. Variation in alkalinity (mg/L as $CaCO_3$) of the mixtures monitored over 63 days.

3.2.5. Variation in Volatile Fatty Acids (VFAs) over the Incubation Period

Figure 6 summarizes the variation in volatile acids monitored over 63 days. The concentration of volatile acids in all mixtures increased and peaked on day 21, indicating that the consumption rate of volatile acids was lower than the generation rate until day 21. The inoculum, already in a nearly stabilized condition, had a relatively constant concentration of volatile acids, indicating negligible methane production over the incubation period. As seen with COD, an extended lag phase was observed with VFAs for the mixtures containing 10% FOG. This delay was likely due to the time required for the digested sludge to acclimate to the complex 10% FOG added to the digesters, rather than to methanogenesis inhibition caused by souring from a rapid buildup of volatile acids, as the digestion process eventually recovered.

Figure 7 describes the variation in the volatile acids/alkalinity ratio over time. Initially, the value climbed until day 28, when nearly all mixtures exceeded the optimal range of 0.1 - 0.3 [25], presumably because hydrolysis and acidogenesis were primarily taking place. On day 42, the ratio of almost all mixtures, including

100% TWAS, dropped below 0.3, indicating a delayed onset of methanogenesis until day 28. Consequently, the elevated ratios observed earlier in the process were likely due to the acclimation time of the microbes to the substrates, with no impending digestion failure expected.

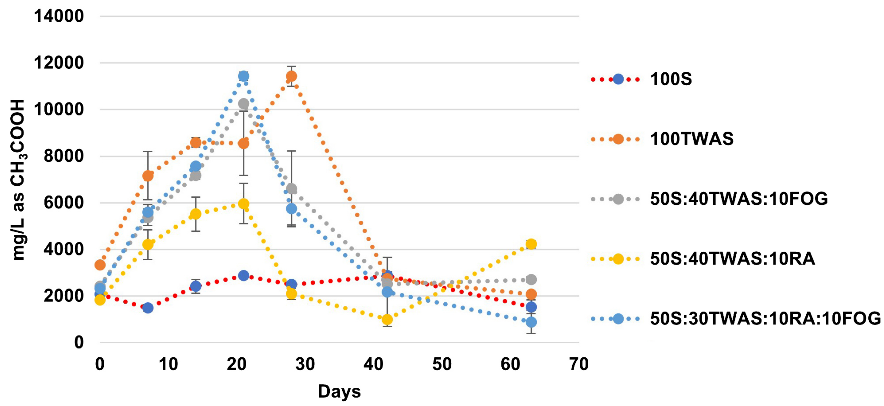


Figure 6. Variation in volatile acids (mg/L as CH_3COOH) of the mixtures monitored over 63 days.

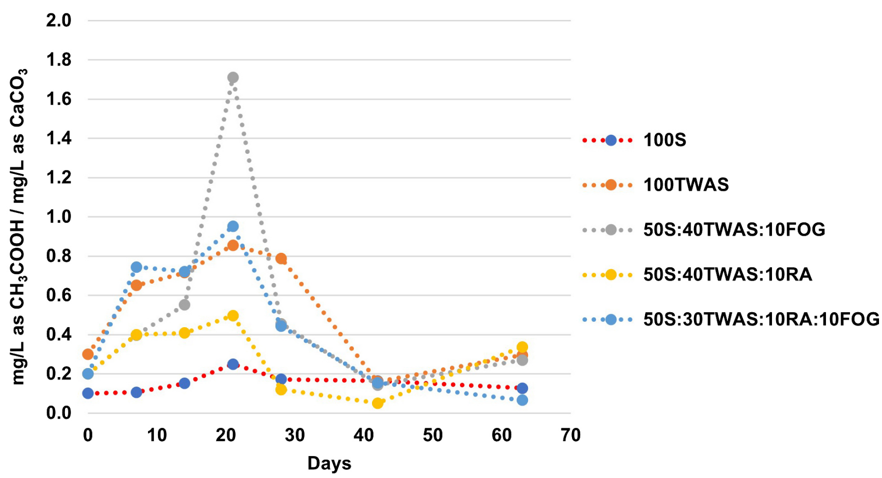


Figure 7. Variation in volatile acids/alkalinity ratio of the mixtures over 63 days.

3.2.6. Variation in pH over the Incubation Period

The pH is a primary factor that can indicate the stability of the anaerobic co-digestion process. Figure 8 illustrates the variation in pH over time. The pH remained stable in the range of 7.5 - 8.5 for the duration of the incubation period. No attempt was made to optimize the bicarbonate addition, but the level can likely be reduced since no signs of souring were observed in any of the experiments.

3.2.7. Variation in Volatile Solids Reduction over the Incubation Period

Figure 9 summarizes the reduction of volatile solids (%) in the mixtures monitored over time. Unlike other parameters, volatile solids were measured only on days 14, 42, and 63. Despite this limitation, the selected time intervals effectively captured the trend in volatile solids reduction, allowing for meaningful interpretation of the results. The volatile solids decreased by a maximum percentage (~85%) for the mixture containing 10% FOG and 10% red apple juicing waste residuals within 63 days of incubation. After day 42, the reduction of volatile solids in the mixtures leveled off, indicating stabilization of the digestion process. Meanwhile, the mixture containing 10% FOG as the single substrate reduced volatile solids by 80.5%. Furthermore, except for the mixture containing 10% FOG combined with 10% red apple juicing waste residuals, slight differences were observed in the volatile solids reduction between 42 and 63 days for the other mixtures. The discrepancy may be attributed to differences in microbial density between the respective mixtures on day 42 and day 63.

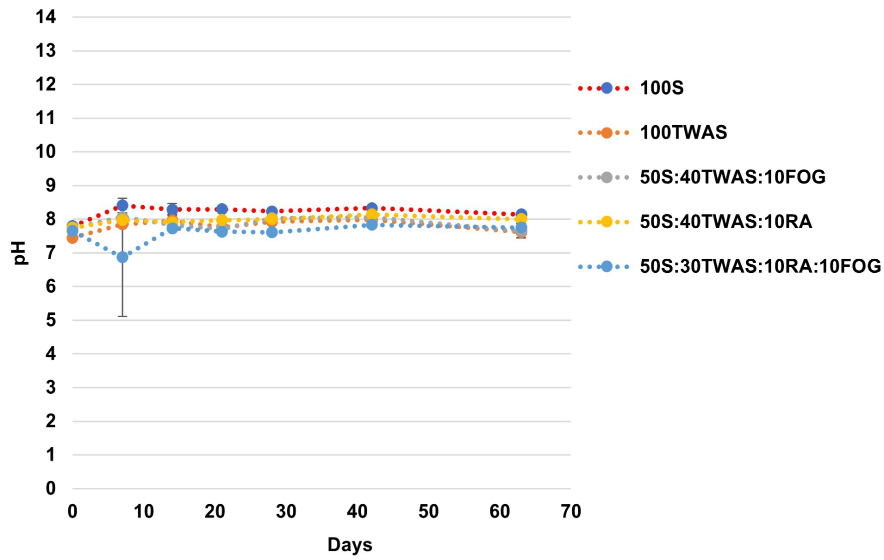


Figure 8. Variation in pH of the mixtures monitored over 63 days.

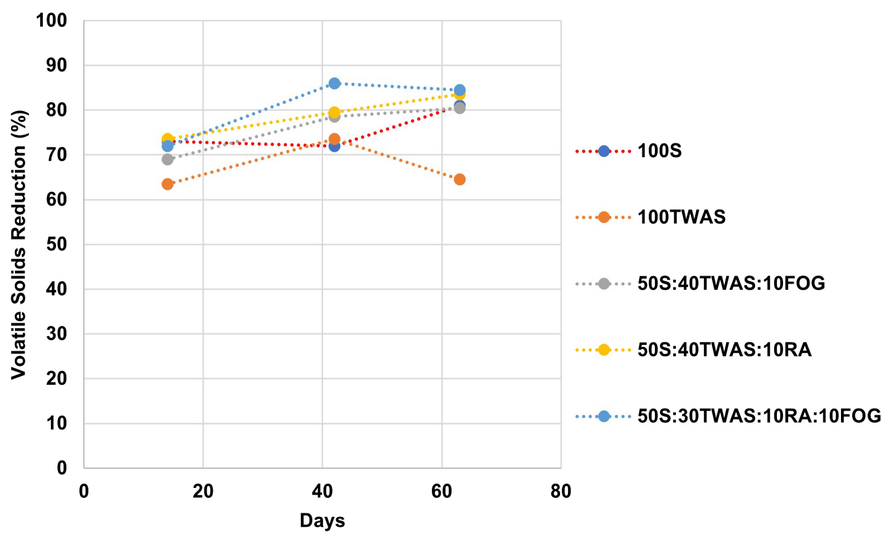


Figure 9. Variation in volatile solids reduction (%) of the mixtures over the incubation period.

3.3. Cumulative Biogas Production Yield

Figure 10 summarizes the variation in cumulative biogas yield over 63 days incubation. Until day 21, the mixture containing red apple juicing waste residuals produced more biogas compared to controls and those containing FOG. This indicates the presence of more readily biodegradable soluble carbohydrates. After 21 days, a linear increase in biogas production was observed for the mixture containing 10% FOG and 10% red apples, suggesting a lag phase of approximately 21 days for biogas production for mixtures with FOG. The observed lag phase may be attributed to the inhibitory effects of LCFAs produced during the degradation of lipids in FOG. It took time for the anaerobic microbial community to acclimate to the complex FOG substrate and its hydrolysis products.

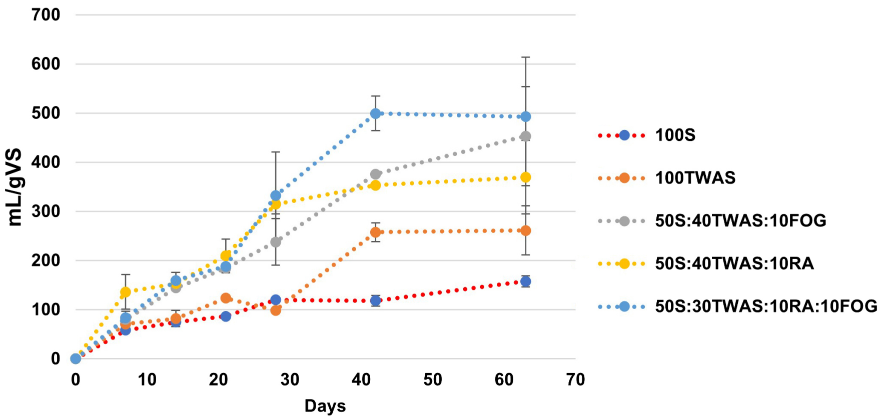


Figure 10. Variation in cumulative biogas production yield (mL/gVS) of the mixtures monitored over 63 days.

The observed lag phase aligns with findings from Usman *et al.* (2020) [58], who reported a 25-day lag phase during anaerobic digestion of FOG, attributed to the initial presence of LCFAs. In the current study, the lag phase was likely caused by physical transport limitations of LCFAs rather than metabolic inhibition. Additionally, insufficient nitrogen purging might have resulted in extending the lag phase by leaving residual oxygen in the headspace, potentially affecting initial microbial activity. Other factors, such as LCFA concentration, inoculum characteristics, and temperature fluctuations, could also have influenced the duration of the lag phase. To mitigate this delay, future studies could explore strategies such as inoculum pre-acclimation, improved nitrogen purging, and bioaugmentation with LCFA-degrading microbes.

Despite the lag phase, Figure 10 shows that the mixture containing 10% FOG had a biogas yield of 453 mL/gVS after 63 days, while the mixture containing 10% FOG along with 10% red apple juicing waste residuals demonstrated an even higher biogas yield of 492 mL/gVS. This yield was 2 - 3 times higher than the controls (e.g., no FOG or fruit waste) and also surpassed the mixture containing only 10% red apple waste (369 mL/gVS). These findings align with Abdallah *et al.* (2022) [59], who noted that lipid-rich substrates can achieve higher methane yields but often exhibit slower hydrolysis kinetics. Similarly, Xue *et al.* (2019) [60] highlighted a positive correlation between biogas production and lipid content in the digester medium.

Although biogas yield trends indicate a lag phase and microbial acclimation, a detailed analysis of the microbial interactions responsible for biogas production and process stabilization was beyond the scope of this study. However, the performance and stability of anaerobic digestion are directly related to the microbial composition involved in the process [61]. Future studies incorporating metagenomic analysis and microbial sequencing could elucidate microbial diversity, community composition, and functional interactions, particularly those involved in LCFA degradation and syntrophic relationships between fermentative bacteria and methanogens. This would provide deeper insights into their roles in anaerobic co-digestion and enhance our understanding of biogas production dynamics during co-digestion.

3.4. Cumulative Methane Production Yield

Figure 11 shows the variation in methane yield over time and demonstrates that the feedstock composition plays a vital role in anaerobic co-digestion performance. The highest recorded methane yield (280 mL/gVS with 55% methane) was obtained for the mixture containing 10% FOG and 10% red apple juicing waste residuals on day 63, after exhibiting a lag phase of 21 days (Figure 11). The methane yield of the inoculum stayed below 50 mL/gVS throughout the incubation period. The methane yield of the mixture containing 10% FOG as the sole substrate started to increase after day 21 and attained stabilization within 63 days with a methane yield of 243 mL/gVS with 53% methane compared to the highest methane yield of 201 mL/gVS obtained by Mahat *et al.* (2020) [36] after SRT = 54 days by mixing substrate rich in lipid content with anaerobic digestate in equal amounts.

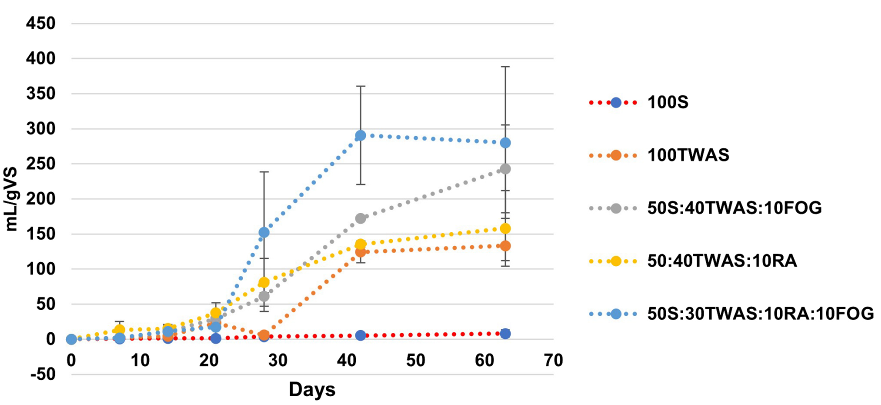


Figure 11. Variation in methane yield (mL/gVS) of the mixtures monitored over 63 days.

It is anticipated that increasing the percentage of FOG (>10%), regardless of whether fruit juicing waste residuals were added, will extend the observed lag phase (>21 days) as the microorganisms need to adapt and degrade even higher concentration of complex LCFAs produced from the hydrolysis of FOG [55] [58] [62]. LCFA intermediates are known inhibitors of nutrient transport and enzyme activity and can damage cell membranes and lead to biomass flotation due to coagulation [11] [55] [63]. While this study focused on a 10% FOG loading rate to balance substrate availability and process stability, further research at higher FOG loadings (>10%) or on optimizing the FOG-to-fruit waste ratio is recommended to better evaluate microbial adaptation and system performance during process scale-up. Specifically, future studies could increase FOG loading rates from 10% to 30%, while varying fruit waste ratios to observe their influence on methane yield without compromising the process stability. Such research would provide valuable insights for scaling up anaerobic digestion systems to handle high-strength organic waste streams in industrial settings. Despite this, FOG addition increased methane yield more than simply adding red apple juicing waste residuals alone since FOG lipids typically have a higher energy density (700 - 1430 mL CH_4/gVS; [64]) than carbohydrates from fruit waste (160 - 350 mL CH_4/gVS; [65]). **Figure 11** shows that replacing 10% of red apple juicing waste residuals with 10% of FOG increased the methane yield from 158 mL/gVS to 243 mL/gVS.

Conversely, **Figure 11** also shows that using red apple juicing waste residuals as the sole substrate resulted in a higher methane yield of 158 mL/gVS compared to the TWAS control (133 mL/gVS). This difference can be attributed to the presence of complex extracellular polymeric substances with low biodegradability in the TWAS control, making it resistant to anaerobic co-digestion, resulting in reduced methane production [66]. In contrast, the presence of 10% red apple juicing waste residuals in the waste slurry, with its aqueous composition and simpler structure, enhanced the biodegradability and made it easier for the microbial fauna to access the soluble sugars (fructose, sucrose, glucose, and sorbitol) and increase methane yield. However, the rapid exhaustion of these readily accessible carbon sources might have resulted in the marginal observed increase in the methane yield compared to the TWAS control.

An interesting observation was that the combination of red apple juicing waste residuals and FOG resulted in the highest methane yield measured (280 mL/gVS), twice as much as the TWAS control. The mix of nitrogen-rich TWAS with lipid-rich FOG and carbohydrate-rich fruit juicing waste residuals of the red apple variety were compatible and increased the methane yield. The simple sugars present in the fruit juicing waste residuals may have provided more bioavailable carbon to increase the microbial growth rates supported by the presence of high energy density lipids from the FOG. The red apple waste offered rapidly digestible carbohydrates as an energy source, thereby increasing the biogas production rate and improving the reaction kinetics. Meanwhile, FOG's lipid content provided a slower released, more sustained source of carbon. Together, these two substrates created a more stable process and continuous methane production. Additionally, adding 10% red apple waste slurry might have aided in physically dispersing the

FOG more evenly inside the digester, thereby increasing the bio accessibility of FOG for degradation. In addition, the presence of red apple waste likely enhanced the microbial diversity and density, increasing the robustness of the digestion process. Therefore, the combined recipe created an environment favorable for methanogenic growth by enhancing buffering capacity, diluting potential toxins, providing essential nutrient supplementation, and establishing more balanced conditions for anaerobic co-digestion. Figure S2 shows that the combined mixture (50S:30TWAS:10RA:10FOG) produced more methane compared to a similar study conducted by Mahat *et al.* (2020) [36], who used feedstock containing food processing wastewater (FPW) and anaerobic sludge mixed at a ratio of 1:1 (50 mL:50 mL) with a value of 201 mL/gVS.

3.5. Siloxane Results

High-strength organic substrates, such as fruit juicing waste residuals, are generally not expected to generate siloxane compounds, precursors, or derivatives during anaerobic co-digestion. This inference is based on the fact that siloxanes are typically used in personal care products and industrial applications, such as fuel additives and antifoaming agents [67], which are unlikely to be present in fruit waste streams. However, there are various pathways through which siloxane compounds can contaminate feedstock—for example, siloxane-containing pesticides or siloxane-based cleaning agents. Figure 12 summarizes the total siloxane concentration and the concentration of octamethylcyclotetrasiloxane (D4) in the biogas of several mixtures after 30 days of co-digestion under mesophilic conditions. D4 and D5 are the most prevalent form of siloxanes in biogas, which typically comprise 90% of the total siloxanes in biogas [68]. D4 comprised approximately 60% of the total siloxanes in this study.

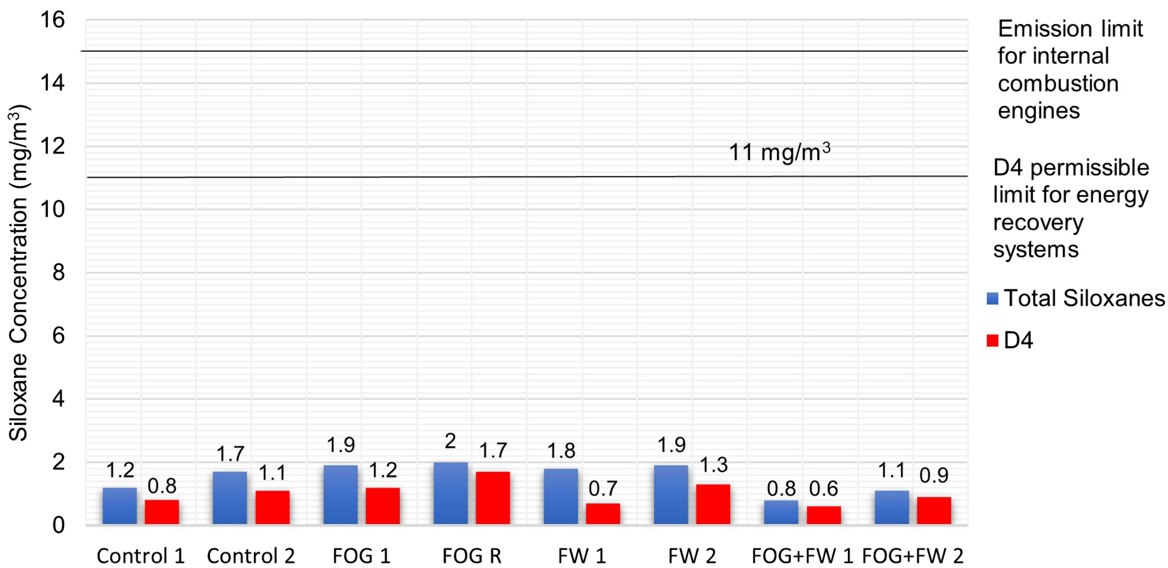


Figure 12. Concentration of octamethylcyclotetrasiloxane (D4) in comparison to total siloxane concentration of the mixtures (mg/m^3).

Figure 12 shows that all siloxane levels measured in this study were below 2 mg/m^3, which did not exceed the emission limit for internal combustion engines (15 mg/m^3) or thermoelectric units in Germany (6 mg/m^3). However, all biogas samples analyzed had siloxane concentrations higher than 0.1 mg/m^3, the recommended limit for biogas intended to be used in turbines and fuel cells. A more stringent limit is established for turbines owing to their greater susceptibility to siloxane damage [69]. With respect to the emission limit for internal combustion engines (15 mg/m^3), there was barely any variation in siloxane levels across the control and the mixtures, as the concentrations remained consistently below 2 mg/m^3, ranging from 0.8 - 2 mg/m^3. D4 concentrations in all biogas samples were below the permissible limit of 11 mg/m^3 for energy recovery systems [70]. Thus, addition of high-strength organic wastes for co-digestion with TWAS did not increase the siloxane concentrations such that no additional costs would be expected for siloxane removal from co-digested derived biogas.

3.6. CoEAT Model

For the CoEAT model input in this study, the biogas production potential value was determined from the batch biodegradability tests to be 15 ft^3/lb (0.94 m^3/kg) of volatile solids destroyed obtained for the 10% FOG and 10% red apple juicing residuals waste slurry. The financial outputs for the two scenarios from the CoEAT model are summarized in **Table S2**. The net benefit will be positive after 15 years, suggesting the implementation of co-digestion at an existing wastewater treatment plant as a long-term investment expected to have a net positive benefit with $39,472 and $52,488 for scenarios 1 and 2, respectively. The analysis assumes that 10 - 18 tons/day of food waste will be diverted from landfills. It has been reported that a 10% food waste addition to the digester feed marginally increases sludge volume production due to the high biodegradability of food waste (volatile solids reduction > 85%), while a 50% addition could lead to a 24% increase in dried sludge mass, potentially raising operational costs and necessitating further analysis of increased sludge handling and disposal costs [71]. Using a 5% interest rate and a 15-year planning horizon, the cost per ton of food waste was determined to be $220/ton for scenario 1 and $114/ton for scenario 2.

We also investigated the cost of an annual subscription service based on 50 clients providing 50 tpy of waste. For scenario 1, a $160/ton subscription yields +$81,000 net benefit; scenario 2, a $120/ton subscription provides +$240,000 net benefit. We did not account for avoided landfill air space savings (estimated broadly at $100 - $400/ton but varies by location, available space, and landfill age), flow control issues, or costs associated with an additional 20% - 25% more biosolids disposal volume.

4. Conclusion

The results of this study revealed that co-digesting high-strength organic wastes could be a viable technique for the efficient management of organic wastes and the production of renewable energy. Anaerobic co-digestion of high-strength organic wastes such as red apple juicing waste residuals and FOG with TWAS can redirect food waste from landfills while increasing biogas and methane production. The ultimate digestibility tests showed that red apple juicing waste residuals alone produced more methane than the control, but FOG alone produced even more. Combining red apple juicing waste residuals and FOG was observed to be particularly advantageous in boosting the methane yield. Co-digestion of both waste types with TWAS enhanced the methane yield from 133 mL/gVS to 280 mL/gVS compared to the TWAS control under mesophilic conditions with SRT = 63 days, with essentially no change in the siloxane concentration. Additionally, the comprehensive analysis of the economic factors indicates that, after a payback period of approximately 15 years with an interest rate of 5%, the co-digestion facility will begin generating profit, demonstrating the promising financial feasibility of implementing a food waste diversion program that takes advantage of excess digester capacity at an existing wastewater treatment facility at an organic diversion rate of 10 - 18 tons/day from the landfills. Smaller additions of food waste (<10%) will result in negligible change in operational parameters. However, with higher food waste additions (>50%), additional operational costs must be accounted for due to the greater volume of sludge production. The CoEAT model's prediction of an organic diversion rate of 10 - 18 tons/day from landfills suggests that food waste additions to the digesters are likely to remain below 10%. While this is expected to result in negligible changes to operational parameters, a more rigorous evaluation is needed to determine the optimal food waste additions to the digesters, maximizing organic diversion and biogas yield while minimizing operational costs. This study specifically focused on red apple waste to maintain substrate compositional consistency and ensure a well-controlled analysis of its impact on anaerobic digestion. The explicit selection of high-performance red apple waste over other available fruit wastes (lemons or pears) ensured that the observed influence on methane yield was directly attributable to the characteristics of this specific fruit waste. While this approach allowed for a comprehensive investigation of the specific feedstock, we acknowledge that the inclusion of other fruit wastes or mixed fruit waste streams would enhance the generalizability of these findings. Future studies incorporating a broader range of lipid-rich and carbohydrate-rich feedstocks, including mixed fruit waste streams, are recommended to validate these results and further explore the potential of high-strength organic feedstocks for improving methane yield during anaerobic co-digestion. Therefore, future research should explore the variability in composition and behavior of different fruit wastes to establish broader applicability.

Authors' Contributions

Sumaiya Sharmin: Investigation, Methodology, Writing-Original Draft, Formal Analysis, Visualization. **Daniel E. Meeroff**: Conceptualization, Supervision, Funding Acquisition, Writing-Review & Editing. **Lusnel Ferdinand**: Methodology, Siloxanes Testing. **Frederick Bloetscher**: Validation, Quality Control, Writing-Reviewing & Editing. **Masoud Jahandar Lashaki**: Resources.

Acknowledgement

Funding Statement: The authors wish to acknowledge the funding support provided by the United States Environmental Protection Agency, Region-4 under Grant No. X1-02D00421-0, LSASD Project Number 21-0372. Additionally, the authors acknowledge Dr. Lanette Sobel and Royce Rose from Raw Juce Company and Steve Roberge from City of Boca Raton Utility Services for providing their support in feedstock collection.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Schieber, H. (2018) Food Waste Is a Big Problem: Here's Why. Schieber Research. https://researchci.com/food-waste-is-a-big-problem-heres-why/

[2] Grandhi, B. and Appaiah Singh, J. (2015) What a Waste! A Study of Food Wastage Behavior in Singapore. *Journal of Food Products Marketing*, **22**, 471-485. https://doi.org/10.1080/10454446.2014.885863

[3] Davis, J. (2022) Food Waste in the United States. Ballard Brief. https://ballardbrief.byu.edu/issue-briefs/food-waste-in-the-united-states

[4] United States Environmental Protection Agency (2018) National Overview: Facts and Figures on Materials, Wastes, and Recycling. EPA. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials

[5] United States Environmental Protection Agency (2023) Quantifying Methane Emissions from Landfilled Food Waste (EPA Report No. EPA-600-R-23-064). https://www.epa.gov/system/files/documents/2023-10/food-waste-landfill-methane-10-8-23-final_508-compliant.pdf

[6] Deer, R. (2021) Landfills: We're Running Out of Space. RoadRunnerWM. https://www.roadrunnerwm.com/blog/landfills-were-running-out-of-space

[7] United States Environmental Protection Agency (2023) Importance of Methane. EPA. https://www.epa.gov/gmi/importance-methane

[8] Dioha, I., Ikeme, C.H. and Nafiu, T. (2013) Effect of Carbon to Nitrogen Ratio on Biogas Production. *International Research Journal of Natural Sciences*, **1**, 1-10. https://www.eajournals.org/wp-content/uploads/EFFECT-OF-CARBON-TO-NITROGEN-RATIO-ON-BIOGAS-PRODUCTION.pdf

[9] High Strength Organic Waste for Co-Digestion Guideline (2024) https://www.sawater.com.au/__data/assets/pdf_file/0006/200859/High-Strength-Organic-Waste-for-Co-digestion-Guideline.pdf

[10] Slopiecka, K., Liberti, F., Massoli, S., Bartocci, P. and Fantozzi, F. (2022) Chemical and Physical Characterization of Food Waste to Improve Its Use in Anaerobic Digestion Plants. *Energy Nexus*, **5**, Article 100049. https://doi.org/10.1016/j.nexus.2022.100049

[11] Salama, E.-S., Saha, S., Kurade, M.B., Dev, S., Chang, S.W. and Jeon, B.-H. (2019)

Recent Trends in Anaerobic Co-Digestion: Fat, Oil, and Grease (FOG) for Enhanced Bio Methanation. *Progress in Energy and Combustion Science*, **70**, 22-42. https://doi.org/10.1016/j.pecs.2018.08.002

[12] Lv, Y.Y., Chang, N., Li, Y.Y. and Liu, J.Y. (2021) Anaerobic Co-Digestion of Food Waste with Municipal Solid Waste Leachate: A Review and Prospective Application with More Benefits. *Resources, Conservation and Recycling*, **174**, 105832-105832. https://doi.org/10.1016/j.resconrec.2021.105832

[13] Tandukar, M. and Pavlostathis, S.G. (2022) Anaerobic Co-Digestion of Municipal Sludge with Fat-Oil-Grease (FOG) Enhances the Destruction of Sludge Solids. *Chemosphere*, **292**, Article 133530. https://doi.org/10.1016/j.chemosphere.2022.133530

[14] Aromolaran, A., Sartaj, M. and Abdallah, M. (2023) Supplemental Sewage Scum and Organic Municipal Solid Waste Addition to the Anaerobic Digestion of Thickened Waste Activated Sludge: Biomethane Potential and Microbiome Analysis. *Fermentation*, 9, Article 237. https://doi.org/10.3390/fermentation9030237

[15] Mato, F.A., Peña, M. García-Rodríguez, Y. Bermejo, M.-D. and Ángel Martín. (2021) Analysis of the Energy Flow in a Municipal Wastewater Treatment Plant Based on a Supercritical Water Oxidation Reactor Coupled to a Gas Turbine. *Processes*, **9**, Article 1237. https://doi.org/10.3390/pr9071237

[16] U.S. Environmental Protection Agency (2016) Anaerobic Digestion: Co-Digestion. U.S. EPA. https://archive.epa.gov/region9/organics/web/html/codigest.html

[17] Chiu, S.L.H. and Lo, I.M.C. (2016) Reviewing the Anaerobic Digestion and Co-Digestion Process of Food Waste from the Perspectives on Biogas Production Performance and Environmental Impacts. *Environmental Science and Pollution Research*, **23**, 24435-24450. https://doi.org/10.1007/s11356-016-7159-2

[18] Siddique, M.N.I. and Wahid, Z.A. (2018) Achievements and Perspectives of Anaerobic Co-Digestion: A Review. *Journal of Cleaner Production*, **194**, 359-371. https://doi.org/10.1016/j.jclepro.2018.05.155

[19] Nghiem, L.D., Koch, K., Bolzonella, D. and Drewes, J.E. (2017) Full Scale Co-Digestion of Wastewater Sludge and Food Waste: Bottlenecks and Possibilities. *Renewable and Sustainable Energy Reviews*, **72**, 354-362. https://doi.org/10.1016/j.rser.2017.01.062

[20] Williams, T.R., Gupta, R., Tasser, C., Appleton, R., Puente, P., Raskin, L., Schaum, C. and Bettina, S. (2023) The Relevance of Food Waste Quality for Co-Digestion Facility Planning, Design, and Operation. The Water Research Foundation. https://www.waterrf.org/resource/relevance-food-waste-quality-co-digestion-facility-planning-design-and-operation

[21] Labatut, R.A., Angenent, L.T. and Scott, N.R. (2014) Conventional Mesophilic VS. Thermophilic Anaerobic Digestion: A Trade-Off between Performance and Stability? *Water Research*, **53**, 249-258. https://doi.org/10.1016/j.watres.2014.01.035

[22] Mao, C., Feng, Y., Wang, X. and Ren, G. (2015) Review on Research Achievements of Biogas from Anaerobic Digestion. *Renewable and Sustainable Energy Reviews*, **45**, 540-555. https://doi.org/10.1016/j.rser.2015.02.032

[23] Nagarajan, S., Jones, R.J., Oram, L., Massanet-Nicolau, J. and Guwy, A. (2022) Intensification of Acidogenic Fermentation for the Production of Biohydrogen and Volatile Fatty Acids—A Perspective. *Fermentation*, **8**, Article 325. https://doi.org/10.3390/fermentation8070325

[24] Filer, J., Ding, H.H. and Chang, S. (2019) Biochemical Methane Potential (BMP) Assay Method for Anaerobic Digestion Research. *Water*, **11**, Article 921.

https://doi.org/10.3390/w11050921

[25] Schnaars, K. (2012) What Every Operator Should Know about Anaerobic Digestion. https://www.wef.org/globalassets/assets-wef/direct-download-library/public/operator-essentials/wet-operator-essentials---anaerobic-digestion---dec12.pdf

[26] Chen, Y., Cheng, J.J. and Creamer, K.S. (2008) Inhibition of Anaerobic Digestion Process: A Review. *Bioresource Technology*, **99**, 4044-4064. https://doi.org/10.1016/j.biortech.2007.01.057

[27] Khanal, S.K., Nindhia, T.G.T. and Nitayavardhana, S. (2019) Chapter 11-Biogas from Wastes: Processes and Applications. In: Taherzadeh, M.J., Bolton, K. and Pandey, A., Eds., *Sustainable Resource Recovery and Zero Waste Approaches*, Elsevier B.V., 165-174. https://doi.org/10.1016/B978-0-444-64200-4.00011-6

[28] Karki, R., Chuenchart, W., Surendra, K.C., Shrestha, S., Raskin, L., Sung, S., Hashimoto, A. and Kumar Khanal, S. (2021) Anaerobic Co-Digestion: Current Status and Perspectives. *Bioresource Technology*, **330**, Article 125001. https://doi.org/10.1016/j.biortech.2021.125001

[29] Adebayo, A., Jekayinfa, S. and Linke, B. (2015) Effects of Organic Loading Rate on Biogas Yield in a Continuously Stirred Tank Reactor Experiment at Mesophilic Temperature. *Current Journal of Applied Science and Technology*, **11**, 1-9. https://doi.org/10.9734/BJAST/2015/18040

[30] He, X., Iasmin, M., Dean, L.O., Lappi, S.E., Ducoste, J.J. and de los Reyes III, F.L. (2011) Evidence for Fat, Oil, and Grease (FOG) Deposit Formation Mechanisms in Sewer Lines. *Environmental Science & Technology*, **45**, 4385-4391. https://doi.org/10.1021/es2001997

[31] Henriksson, J. (2016) Characterization of Composition of the Fat-Rich Residues from Grease Separators. Degree Project, DiVA. http://www.diva-portal.se/smash/get/diva2:944380/FULLTEXT01.pdf

[32] Wang, L., Aziz, T.N. and de los Reyes III, F.L. (2013) Determining the Limits of Anaerobic Co-Digestion of Thickened Waste Activated Sludge with Grease Interceptor Waste. *Water Research*, **47**, 3835-3844. https://doi.org/10.1016/j.watres.2013.04.003

[33] Hao, J., de los Reyes III, F.L. and He, X. (2020) Fat, Oil, and Grease (FOG) Deposits Yield Higher Methane than FOG in Anaerobic Co-Digestion with Waste Activated Sludge. *Journal of Environmental Management*, **268**, Article 110708. https://doi.org/10.1016/j.jenvman.2020.110708

[34] Yusuf, H.H., Roddick, F., Jegatheesan, V., Gao, L. and Pramanik, B.K. (2023) Tackling Fat, Oil, and Grease (FOG) Build-Up in Sewers: Insights into Deposit Formation and Sustainable in-Sewer Management Techniques. *Science of the Total Environment*, **904**, Article 166761. https://doi.org/10.1016/j.scitotenv.2023.166761

[35] Wallace, T., Gibbons, D., O'Dwyer, M. and Curran, T.P. (2017) International Evolution of Fat, Oil and Grease (FOG) Waste Management-A Review. *Journal of Environmental Management*, **187**, 424-435. https://doi.org/10.1016/j.jenvman.2016.11.003

[36] Mahat, S.B., Omar, R., Man, H.C., Idris, A.I.M., Kamal, S.M.M., Idris, A. and Anuar, N.K. (2020) Influence of Substrate to Inoculum Ratio (S/I) on the Treatment Performance of Food Processing Wastewater Containing High Oil and Grease (O&G) in Batch Mode. *Desalination and Water Treatment*, **203**, 267-278. https://doi.org/10.5004/dwt.2020.26231

[37] Ziels, R.M., Karlsson, A., Beck, D.A.C., Ejlertsson, J., Yekta, S.S., Bjorn, A., Stensel, H.D. and Svensson, B.H. (2016) Microbial Community Adaptation Influences Long-

chain Fatty Acid Conversion during Anaerobic Codigestion of Fats, Oils, and Grease with Municipal Sludge. *Water Research*, **103**, 372-382. https://doi.org/10.1016/j.watres.2016.07.043

[38] El Mashad, H. and Zhang, R. (2020) Biogas Energy from Organic Wastes. In: Holden, N.M., Wolfe, M.L., Ogejo, J.A. and Cummins, E.J., Eds., *Introduction to Biosystems Engineering*, American Society of Agricultural and Biological Engineers (ASABE) and Virginia Tech Publishing, 49-71.

[39] Collin, T., Cunningham, R., Jefferson, B. and Villa, R. (2020) Characterisation and Energy Assessment of Fats, Oils and Greases (FOG) Waste at Catchment Level. *Waste Management*, **103**, 399-406. https://doi.org/10.1016/j.wasman.2019.12.040

[40] Salama, E.-S., Jeon, B.-H., Kurade, M.B., Patil, S.M., Usman, M., Li, X. and Lim, H. (2020) Enhanced Anaerobic Co-Digestion of Fat, Oil, and Grease by Calcium Addition: Boost of Biomethane Production and Microbial Community Shift. *Bioresource Technology*, **296**, Article 122353. https://doi.org/10.1016/j.biortech.2019.122353

[41] Long, J.H., Aziz, T.N., de los Reyes III, F.L. and Ducoste, J.J. (2012) Anaerobic Co-Digestion of Fat, Oil, and Grease (FOG): A Review of Gas Production and Process Limitations. *Process Safety and Environmental Protection*, **90**, 231-245. https://doi.org/10.1016/j.psep.2011.10.001

[42] Leong, Y.K. and Chang, J.S. (2022) Valorization of Fruit Wastes for Circular Bioeconomy: Current Advances, Challenges, and Opportunities. *Bioresource Technology*, **359**, Article 127459. https://doi.org/10.1016/j.biortech.2022.127459

[43] Lyu, F., Luiz, S.F., Azeredo, D.R.P., Cruz, A.G., Ajlouni, S. and Ranadheera, C.S. (2020) Apple Pomace as a Functional and Healthy Ingredient in food Products: A Review. *Processes*, **8**, Article 319. https://doi.org/10.3390/pr8030319

[44] Ambaye, T.G., Rene, E.R., Dupont, C., Wongrod, S. and van Hullebusch, E.D. (2020) Anaerobic Digestion of Fruit Waste Mixed with Sewage Sludge Digestate Biochar: Influence on Biomethane Production. *Frontiers in Energy Research*, **8**, Article 31. https://doi.org/10.3389/fenrg.2020.00031

[45] Worrell, W.A., Vesilind, P.A. and Ludwig, C. (2016) Solid Waste Engineering: A Global Perspective. Cengage Learning.

[46] Mrosso, R., Kiplagat, J. and Mecha, A.C. (2023) Anaerobic Codigestion of Tuber Waste and Fruit Waste: Synergy and Enhanced Biogas Production. *International Journal of Chemical Engineering*, **2023**, Article ID: 6637249. https://doi.org/10.1155/2023/6637249

[47] Valença, R.B., dos Santos, L.A., Firmo, A.L.B., da Silva, L.C.S., de Lucena, T.V., *et al.* (2021) Influence of Sodium Bicarbonate ($NaHCO_3$) on the Methane Generation Potential of Organic Food Waste. *Journal of Cleaner Production*, **317**, Article 128390. https://doi.org/10.1016/j.jclepro.2021.128390

[48] Hallaji, S.M., Kuroshkarim, M. and Moussavi, S.P. (2019) Enhancing Methane Production Using Anaerobic Co-Digestion of Waste Activated Sludge with Combined Fruit Waste and Cheese Whey. *BMC Biotechnology*, **19**, Article 13. https://doi.org/10.1186/s12896-019-0513-y

[49] Werkneh, A.A. (2022) Biogas Impurities: Environmental and Health Implications, Removal Technologies, and Future Perspectives. *Heliyon*, **8**, e10929. https://doi.org/10.1016/j.heliyon.2022.e10929

[50] Vali, S.A., Moral-Vico, J., Font, X. and Sánchez, A. (2023) Adsorptive Removal of Siloxanes from Biogas: Recent Advances in Catalyst Reusability and Water Content Effect. *Biomass Conversion and Biorefinery*, **14**, 23259–23273.

https://doi.org/10.1007/s13399-023-04478-1

[51] Lipps, W.C., Braun-Howland, E.B. and Baxter, T.E. (2023) Standard Methods for the Examination of Water and Wastewater.24th edition, APHA Press.

[52] Muller, C., Lam, P., Lin, E., Chapman, T., Devin-Clark, D., Belknap-Williamson, J. and Krugel, S. (2010) Co-Digestion at Annacis Island WWTP: Metro Vancouver's Path to Renewable Energy and Greenhouse Gas Emission Reductions. *Proceedings of the Water Environment Federation*, January 2010, 2706-2722.

[53] United States Environmental Protection Agency (2010) Anaerobic Digestion Tools and Resources. https://19january2017snapshot.epa.gov/anaerobic-digestion/anaerobic-digestion-tools-and-resources_.html

[54] Misheloff, R. (2024) How Much Does It Cost to Lease a Used Dump Truck? SmarterFinanceUSA. https://www.smarterfinanceusa.com/blog/cost-lease-used-dump-truck

[55] Sharmin, S. (2023) Support for Regional Community Anaerobic Digestion for Organic Waste Diversion (Order No. 30635246). Dissertations & Theses @ Florida Atlantic University-FCLA.
https://www.researchgate.net/publication/374081862_Support_for_Regional_Community_Anaerobic_Digestion_for_Organic_Waste_Diversion

[56] Ogundare, O.J. (2020) Potential Recovery of Biogas from Citrus Auranttfolia Waste (Lime Waste). Master's Thesis, Covenant University.

[57] Chuchat, N. and Skolpap, W. (2015) Biogas Production from Poultry Slaughter House and Food Processing Wastes by Microwave Thermal Pretreatment. *Chiang Mai Journal of Science*, **42**, 456-468.

[58] Usman, M., Salama, E.-S., Arif, M., Jeon, B.-H. and Li, X. (2020) Determination of the Inhibitory Concentration Level of Fat, Oil, and Grease (FOG) towards Bacterial and Archaeal Communities in Anaerobic Digestion. *Renewable and Sustainable Energy Reviews*, **131**, Article 110032. https://doi.org/10.1016/j.rser.2020.110032

[59] Abdallah, M., Greige, S., Beyenal, H., Harb, M. and Wazne, M. (2022) Investigating Microbial Dynamics and Potential Advantages of Anaerobic Co-Digestion of Cheese Whey and Poultry Slaughterhouse Wastewaters. *Scientific Reports*, **12**, Article No. 10529. https://doi.org/10.1038/s41598-022-14425-1

[60] Xue, S., Zhao, N., Song, J. and Wang, X. (2019) Interactive Effects of Chemical Composition of Food Waste During Anaerobic Co-Digestion under Thermophilic Temperature. *Sustainability*, **11**, Article 2933. https://doi.org/10.3390/su11102933

[61] Kim, N.-K., Lee, S.-H., Kim, Y. and Park, H.-D. (2022) Current Understanding and Perspectives in Anaerobic Digestion Based on Genome-Resolved Metagenomic Approaches. *Bioresource Technology*, **344**, Article 126350.
https://doi.org/10.1016/j.biortech.2021.126350

[62] Sethi, R. (2018) Biogas Production from Organic Waste, Meat, and Fog by Anaerobic Digestion and Ultimate Sludge Digestibility. Master's Thesis, Florida Atlantic University.

[63] Sun, M., Shi, Z., Zhang, C., Zhang, Y., Zhang, S. and Luo, G. (2022) Novel Long-Chain Fatty Acid (LCFA)-Degrading Bacteria and Pathways in Anaerobic Digestion Promoted by Hydrochar as Revealed by Genome-Centric Metatranscriptomics Analysis. *Applied and Environmental Microbiology*, **88**, e01042-e01022.
https://doi.org/10.1128/aem.01042-22

[64] Azarmanesh, R., Zarghami Qaretapeh, M., Hasani Zonoozi, M., Ghiasinejad, H. and Zhang, Y. (2023) Anaerobic Co-Digestion of Sewage Sludge with Other Organic Wastes: A Comprehensive Review Focusing on Selection Criteria, Operational

Conditions, and Microbiology. *Chemical Engineering Journal Advances*, **14**, Article 100453. https://doi.org/10.1016/j.ceja.2023.100453

[65] Czubaszek, R., Wysocka-Czubaszek, A. and Tyborowski, R. (2022) Methane Production Potential from Apple Pomace, Cabbage Leaves, Pumpkin Residue, and Walnut husks. *Applied Sciences*, **12**, Article 6128. https://doi.org/10.3390/app12126128

[66] Zhang, L., Peng, B., Wang, L. and Wang, Q. (2022) Potential of Anaerobic Co-Digestion of Acidic Fruit Processing Waste and Waste-Activated Sludge for Biogas Production. *Green Processing and Synthesis*, **11**, 1013-1025. https://doi.org/10.1515/gps-2022-0089

[67] Zhang, Z., Qi, H., Ren, N., Li, Y., Gao, D. and Kannan, K. (2010) Survey of Cyclic and Linear Siloxanes in Sediment from the Songhua River and in Sewage Sludge from Wastewater Treatment Plants, Northeastern China. *Archives of Environmental Contamination and Toxicology*, **60**, 204-211. https://doi.org/10.1007/s00244-010-9619-x

[68] Wang, J., Liao, L., Wang, L. and Wang, L. (2022) Influence of Sampling Methods and Storage Condition on Volatile Methyl Siloxanes Quantification in Biogas. *Biomass and Bioenergy*, **158**, Article 106347. https://doi.org/10.1016/j.biombioe.2022.106347

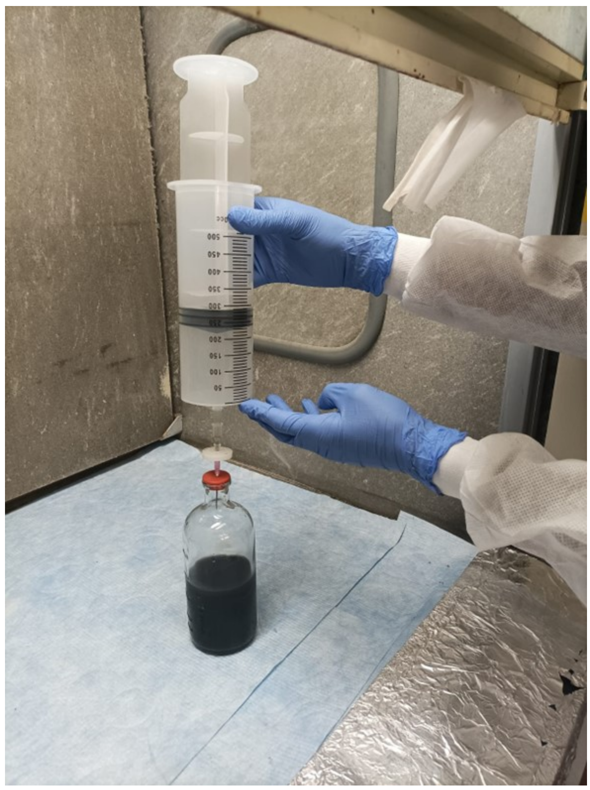
[69] Ruiling, G., Shikun, C. and Zifu, L. (2017) Research Progress of Siloxane Removal from Biogas. *International Journal of Agricultural and Biological Engineering*, **10**, 30-39.

[70] Noshadi, I., Kanjilal, B., Jafari, T., Moharreri, E., Khakpash, N., Jiang, T. and Suib, S. L. (2016) Hydrophobic Mesoporous Adsorbent Based on Cyclic Amine-Divinylbenzene Copolymer for Highly Efficient Siloxane Removal. *RSC Advances*, **6**, 77310-77320. https://doi.org/10.1039/C6RA11382F

[71] Ellacuriaga, M., González, R. and Gómez, X. (2024) Feasibility of Coupling Hydrogen and Methane Production in WWTP: Simulation of Sludge and Food Wastes Co-Digestion. *Energy Nexus*, **14**, Article 100285. https://doi.org/10.1016/j.nexus.2024.100285

Supporting Information

(a)



(b)

Figure S1. The photographs of the experimental setup. (a) Incubation of the serum bottles in water bath chambers; (b) Measurement of biogas volume using 550 mL plastic syringe.

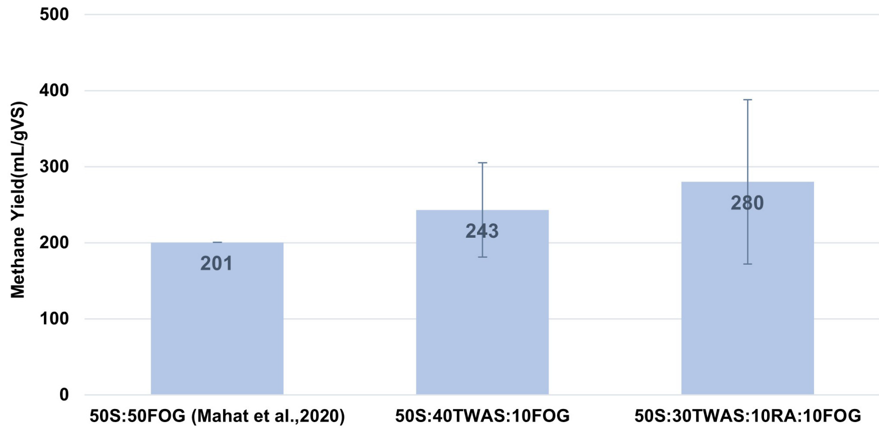


Figure S2. Histogram showing the methane yield (mL/gVS) of the two best-performing mixtures in this study compared to the previous work conducted by Mahat *et al.* (2020) under similar conditions.

Table S1. The chemical characterization of different food waste feedstocks.

Food Waste	Carbohydrates (%)	Proteins (%)	Lipids (%)
Used vegetable oil	0	0	100
FOG from food processing	0	0.2	99.8
FOG from restaurants	0	0.1	99.0
Butter	3.3	13.3	83.4
Cooked eggs	26.5	7.9	65.6
Fish flesh (salmon)	13.7	25.0	61.3
Fruit waste residuals	58 - 94	5.5 - 41	0.2 - 1.7
Vegetable waste	80.8	17.8	1.4

Table S2. Summaries of the CoEAT model results for two scenarios.

Scenario	Net Present Value from CoEAT (2010 version)	Per ton basis	Client Subscription Based on 50 tpy per Client
1) Medium-sized Wastewater Treatment Plant without an existing co-generation facility receiving 10 tpd food waste	+$39,500	$220/ton	+$81,000/yr. (50 clients @$160/ton)
2) Large-sized Wastewater Treatment Plant with existing Co-generation facility receiving 20 tpd food waste	+$52,500	$114/ton	+$240,000/yr. (120 clients @$120/ton)