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Energy Research and Development Division

FINAL PROJECT REPORT

Lowering Costs of Food Waste Codigestion for Renewable Biogas Production

An Innovative Combination of Preprocessing Technique and Strategy for Cake Solids Reduction

Gavin Newsom, Governor
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PREPARED BY:

Primary Authors:
Ganesh Rajagopalan, Ph.D., PE, BCEE
Bhargavi Subramanian, Ph.D.
Helia Safaee
Ryan Holloway, Ph.D., PE

Kennedy/Jenks Consultants
3200 El Camino Real, #200
Irvine, CA 92602
Phone: 949-567-2162
www.kennedyjenks.com

Contract Number: EPC-14-046

PREPARED FOR:
California Energy Commission

Abolghasem Edalati
Project Manager

Jonah Steinbuck, Ph.D.
Office Manager
ENERGY GENERATION RESEARCH OFFICE

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

DISCLAIMER

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First, the project team thanks California Energy Commission for providing us the opportunity to perform this timely and valuable project. Organic waste, such as food waste from restaurants, households and institutions, are often disposed in landfills where they decay and contribute to greenhouse gas emissions. Diverting organic materials from landfills for generating alternate energy at wastewater treatment plants in an economical manner that will significantly benefit our environment.

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Lowering Costs of Food Waste Codigestion for Renewable Biogas Production is the final report for the Lowering Food Waste Codigestion Costs project (Contract Number EPC-14-046) conducted by Kennedy Jenks Consultants. The information from this project contributes to Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

This project demonstrated a new technology to lower the preprocessing cost of food wastes and a new strategy to add fats, oil, and grease or pre-processed food wastes for anaerobic digestion with wastewater sludge (codigestion). These two steps aim to lower dewatered cake requiring disposal, which, in turn, will encourage the diversion of food waste from landfills, and enhance production of digester gas, a renewable energy source. The new technology for the preprocessing of food wastes uses an organic waste separation technique known as an organic extrusion press for selective extrusion of organic materials from inorganic contaminants, based on the differences in their viscosities. The extraction efficiency of this technology is higher than that of conventional, size-based separation techniques predominantly practiced by the industry. Further, since the proposed technology requires minimal preprocessing of the municipal solid waste, it is more economical than typical source separation programs.

Results indicated that preprocessing of food wastes using the organic extrusion press resulted in 54 percent cost savings compared to conventional food wastes separation technique. Economic evaluation of a 100-million-gallons-per-day plant indicated that codigestion of food waste preprocessed using this technology resulted in $8.9 to $9.3 million worth of energy savings due to increased gas production. Codigestion with fats, oils, and grease increased gas production by up to 58 percent compared to the sludge-only digestion. The gas production for every pound of combined sludge and food waste added was 20 percent higher compared to a pound of only sludge fed to the digester. Strategic addition of the food waste improved the percent of solids of the dewatered cake by approximately 13 percent, lowering the net mass of cake requiring disposal by 11.5 percent. The estimated payback period for a 100-million-gallons-per-day wastewater treatment plant to implement codigestion ranged from 4.7 to 5.3 years.

Keywords: Codigestion, food waste, dewatering, gas production, organic extraction press, organic polishing system/paddle finisher, renewable gas, fats, oils and grease

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EXECUTIVE SUMMARY

Introduction

Anaerobic digestion is a process in which microorganisms break down biodegradable materials without using oxygen. The United States Environmental Protection agency estimates that 15 percent to 30 percent of anaerobic digester capacity at 140 wastewater treatment plants in California is underused. A 2009 California Energy Commission (CEC) report, *Combined Heat and Power Potential at California's Wastewater Treatment Plants*, suggests this excess capacity could be used for codigestion of organic wastes to enhance biogas production and increase energy generation in California by 415 megawatts. Codigestion is a process where high strength organic waste materials are added to wastewater digesters with excess capacity. In the past few decades, organic wastes such as food waste and fats, oils, and grease have been identified as additional sources of biogas production when used for codigestion with wastewater solids.

While there are several barriers to implementing a codigestion project, the primary barrier is cost. Of the 140 wastewater treatment plants in California that have anaerobic digesters, fewer than 25 produce power using digester gas (Breunig, Jin, et al. 2017). Although wastewater entities want to recover the energy value of the digester gas by producing electricity, in many instances it is less expensive to flare the gas. Installing a codigestion project requires capital improvements such as construction of a waste receiving and storage facility, digester improvements, and gas collection and treatment control. For many wastewater entities, the revenue from increased biogas production and tipping fees alone may not be enough to pay for the capital improvements in a reasonable time frame. An additional concern with codigestion projects, especially using fats, oils, and grease, is that the availability of the waste stream may be limited, which would undermine the initial capital investment. A 2012 Water Environment Research Foundation study, *Barriers to Biogas Use for Renewable Energy*, identified inadequate payback and economics as the predominant barrier for implementation of biogas programs in wastewater treatment plants (Willis, et al. 2012).

In contrast to fats, oils, and grease, food waste is more widely available to the extent that a capital investment can rely upon its availability as a feedstock for the duration of the project lifespan. However, the food waste received at solid waste processing centers requires that inorganic materials such as cutlery, cans, paper, bags etc. be removed before it can be used for digestion. The current practice to remove these inert materials involves labor-intensive and costly source separation, followed by preprocessing by multiple screening and grinding steps. The challenge in using food waste as a co-waste in wastewater treatment plants is in developing an approach that demonstrates that both food waste preprocessing and digestion are cost-effective.

Project Purpose

The goals of this study are to demonstrate the economic feasibility of establishing food waste codigestion, to encourage the diversion of food waste from landfills, and to recover lost digester gas as an alternative and renewable energy source. The proposed project will demonstrate two novel and complementary approaches to address the economic and technological barriers to codigestion: 1) lowering the cost of food waste preprocessing at waste management facilities, and 2) demonstrating the operation and economic benefits of codigestion at wastewater treatment plants.

While several studies, including CEC Public Interest Energy Research program studies, have demonstrated increases in gas production through codigestion, the studies did not address concurrent improvements to preprocessing of food waste or the effect of codigestion on the quality of digested sludge. The demonstration project in this study intended to simultaneously reduce the preprocessing cost of food waste and the disposal cost of digested sludge to render codigestion economically viable for a larger number of utilities. This, in turn, will significantly increase biogas energy production, as well as lower greenhouse gas emissions from organic wastes that would otherwise be hauled to landfills.

Project Process

This study demonstrated the proposed, novel food waste preprocessing and codigestion strategy using the following approaches:

- Demonstration of food waste preprocessing technique: The proposed technology included a two-step process that combined the efforts of waste management facilities with wastewater treatment plants to extract food waste in a cost-effective manner. Off-site preprocessing of collected municipal solid waste was first performed using an organic extrusion press at a centralized waste management facility (Recology, in San Francisco, California). The organic extrusion press separated organic material from non-digestible inert material through the application of pressure, based on size exclusion and viscosity. This offered a higher potential for improving separation efficiency. The separated food waste was then hauled to the project demonstration site (Silicon Valley Clean Water, Redwood City, California), where further on-site processing was performed using a polishing system prior to digestion.
- Demonstration of strategic food waste addition to lower the mass of dewatered sludge (cake solids) requiring disposal: One of the major costs of wastewater treatment is the cost of disposal of dewatered sludge (that is cake solids) from the digesters. In addition to increased biogas production through food waste addition, another cost reduction method proposed in this project involved the addition of food waste at strategically developed food waste to sludge ratios based on their volatile solids content. Under this loading conditions, through a systematic interaction of food waste and sludge solids, the net mass of dewatered cake requiring disposal is reduced. Digester operation, with wastewater sludge only, was used to establish the benchmark performance for dewatering efficiency and biogas generation. The project team then studied codigestion performance with both fats, oils, and grease and food waste, which were loaded at different volatile solids ratios to the sludge. The effect of adding fats, oils, and grease or food waste was analyzed based on biogas quality and production rate, dewatering efficiency, and other operating parameters. Improvements in revenue streams, energy recovery, or disposal costs for dewatered cake were tracked to demonstrate the operating benefits and drawbacks for the proposed codigestion strategy.

The project team then performed an economic analysis to assess the feasibility of the proposed project with considerations for both the preprocessing and codigestion process.

Project Results

Results from the project indicated that the proposed method for food waste preprocessing using an organic extrusion press and further polishing at the Silicon Valley Clean Water demonstration site, followed by controlled loading of food waste to digesters, is a cost-effective codigestion strategy. The improvements in biogas production (energy recovery), the new revenue stream via tipping fees (costs charged by the wastewater treatment facilities for receiving organic wastes from waste haulers), and the savings generated by the reduced mass of dewatered cake (biosolid disposal costs) make the proposed food waste codigestion program an economically advantageous strategy compared to sludge-only digestion. The reduced cost of food waste preprocessing using the two-step organic extrusion press and polishing technique also makes obtaining this feedstock sustainable. Therefore, the new preprocessing and codigestion method presented in this demonstration project is a viable method for improving wastewater treatment plant operations. Sustainable and renewable sources of energy are made more accessible and food waste is diverted from landfills, reducing greenhouse gas emissions from and the carbon footprint of wastewater treatment plants.

Major highlights of findings from the project demonstration include the following.

Food Waste Pre-Processing Through Organic Extrusion Press

- Organic extrusion press operation was able to process municipal solid waste to extract organic matter.
- An economic analysis on this strategy for food waste extraction showed that costs for organic extrusion press preprocessing is at least 46 percent less expensive than source-separating operations for typical pricing found in the San Francisco Bay Area.

Food Waste Codigestion and Downstream Processing at Wastewater Treatment Plants

The following discussion summarizes the key results obtained at the Silicon Valley Clean Water demonstration site.

- Codigestion using fats, oils, and grease and food waste had a higher percent of volatile solid reduction (64 to 68 percent) during digestion, compared to the benchmark test (sludge-only digestion, ~61 to 63 percent).
- Codigestion using food waste increased the unit gas production (cubic feet biogas produced per pound of volatile solids destroyed) in the digesters from approximately 4 to 22 percent. The higher unit gas production indicated that for the same total volatile solid loading, the addition of food waste can improve biogas production over sludge-only digestion.
- Codigestion using food waste resulted in a higher dewatering efficiency for the produced digester cake (as measured by the percent of solids in dewatered cake), when compared to sludge-only digestion. This, in turn, reduced the volume of

generated biosolids (dewatered cake) by approximately 3 to 18 percent. This reduces dewatered sludge hauling and disposal costs.

- Codigestion using food waste affected cake odor. In general, levels of odor-producing compounds were higher with food waste loading than the benchmarking test but were similar or lower for corresponding fats, oils, and grease tests.
- A payback period of approximately six to eight years was estimated for the capital investment necessary for a 15-million-gallons-per-day plant to implement food waste codigestion and a biogas recovery system. For a 100-million-gallons-per-day plant, the payback period was estimated to be approximately five years. The payback period is heavily dependent on several variables, such as tipping fees, electricity prices, and biosolid disposal costs, all of which can vary from plant to plant.

Technology Transfer Efforts

The findings from this study have already been disseminated to a variety of audiences. To discuss the details and benefits of the preprocessing and codigestion demonstration, the project team developed a comprehensive presentation targeted for industry professionals to share project findings and outcomes. To date, the findings from this study have been presented or accepted for presentation in the following state and nationwide conferences (Table ES-1):

Table ES-1: Conference Presentations of Study Findings

Conference	Date	Presentation Type/Title	Location
WEF Residuals and Biosolids Conference	April 2017	Panel discussion	Seattle, WA
Kennedy/Jenks Client Breakfast Meeting	Dec. 2017	Regional meeting	Sacramento, CA
CWEA Annual Conference	April 2018	Workshop	Sacramento, CA
WEFTEC, 2019	Sep. 2019	Workshop	Chicago, IL
WEFTEC, 2019	Sept. 2019	Podium presentation	Chicago, IL

Source: Kennedy/Jenks Consultants

The abstracts and presentation slides are included in Appendix B, arranged in the same order as in this table.

Benefits to California

In California, 268 wastewater treatment plants each have more than 1-million-gallons-per-day of wastewater treatment capacity. The combined treatment capacity of these plants is approximately 3,000 million gallons per day. To date only about 25 plants produce electricity using digester gas. Implementation of codigestion using technology and strategy can significantly enhance biogas production and energy recovery, reduce greenhouse gas emissions, provide a reliable source of renewable energy and reduce overall carbon footprint. The details of these benefits are described below.

Estimated Increase in Energy Recovery

The estimated energy generation potential through the digestion of all the wastewater sludge from California plants is about 125 megawatts. Based on the results obtained in this study, the proposed project can increase digester gas production by approximately 46 to 70 percent, depending on the food waste to sludge loading. Assuming 30 percent market penetration (based on the current capability of plants for energy recovery and access to feedstock), the proposed approach can enhance bioenergy production by 26 megawatts (approximately 70 wastewater treatment facilities). However, due to the cost-effective nature of the project, it is reasonable to anticipate higher market penetration in the long-run. In addition, this estimate is based on the study results for 25 percent volatile solid loading with food waste. Higher food waste loading is possible and offers a greater potential for energy recovery.

Estimated Reduction in Greenhouse Gas Emissions

Greenhouse gas emission reductions come from diversion of organics from landfills. The proposed study facilitates the use of food waste for biogas energy production rather than disposing of it in landfills. On average, it is estimated that approximately 0.25 pounds of food waste is produced per person per day in the United States. Accordingly, California, with a population of 37 million, produces an estimated volume of 4,100 tons of food waste per day. If the proposed study achieves a 30 percent market penetration, it would eliminate greenhouse gas emissions from approximately 370,000 tons of food waste annually (201,000 metric tons of carbon dioxide equivalent per year). This is based on 25 percent volatile solids loading. Further, it is possible to increase the amount of added food waste and hence, obtain greater benefit.

Reliability of a Renewable Resource

Codigestion provides a reliable source of energy. While there are some seasonal variations (organic content) in wastewater, such variations are much smaller than those with other forms of alternate energies, such as solar and wind. Further, it is fair to expect the overall supply of food waste from collected municipal solid waste to be stable. Assuming the project is replicated at 30 percent market penetration, the diversion of food waste from landfills to anaerobic digesters can sustainably produce approximately 60 megawatts of renewable energy through diversion of approximately 370,000 tons of food waste per year. Since the proposed method is estimated to increase energy supply and reduce operating costs for wastewater treatment plants, ratepayers should not be affected by the project costs.

Estimated Reduction of Carbon Footprint

Carbon footprint reductions come from lowered truck emissions due to reduced solids handling. Based on study results, the implementation of the proposed innovations has the potential to lower the mass of dewatered cake by 45 to 53 percent. The reduced volume of biosolids requiring disposal will lower the emissions from trucks used for hauling sludge to the disposal facility or landfill. At the conservative assumption of 30 percent market penetration, this could result in a reduction of 245,000 wet tons per year in sludge hauling.

CHAPTER 1: Introduction

This chapter provides background on codigestion of food wastes, the project objectives and goals, the scope of the report, and its organization.

1.1 Background

While the primary mission of wastewater treatment plants (WWTPs) is to protect public health, these facilities are being recognized as an increasingly valuable source for clean renewable energy. In California, the estimated energy generation potential through anaerobic digestion (AD) of all wastewater-generated solids is about 125 megawatts (MW) (Breunig, Jin, et al. 2017). In the past few decades, organic wastes such as food waste (FW) and fats, oils, and grease (FOG) have been identified as additional sources of biogas production when used for codigestion with wastewater solids. According to the U.S. Environmental Protection Agency (U.S. EPA), anaerobic digesters are estimated to have 15 – 30 percent of underused capacity at 140 WWTPs in California alone. This excess capacity could be used for codigestion. This is predicted to increase AD energy generation in California to 415 MW (Breunig, Jin, et al. 2017).

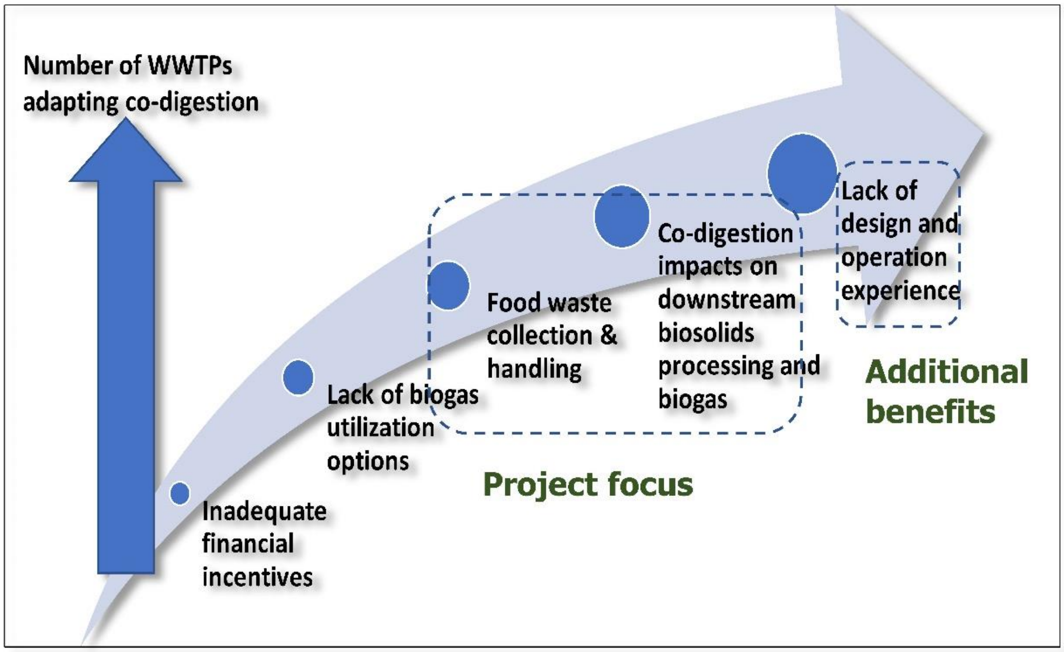
In 2014, the U.S. generated about 38 million tons of municipal FW, a 13 percent increase from 2008. Approximately 95 percent of the generated FW was landfilled. FW releases methane faster than other organic waste and accounts for an estimated 34 to 51 percent of the generated methane escaping landfills (Breunig, Jin, et al. 2017). The increasing production of FW and its landfill disposal contributes to greenhouse gas (GHG) emissions, occupies land, and prevents reclaiming of energy resources that would otherwise fulfill a circular economy. Life-cycle assessments of incineration, composting, AD, and landfill treatment technologies for FW have shown that AD provides the greatest reduction in carbon dioxide emissions when the generated biogas is captured and used for energy (Breunig, Jin, et al. 2017).

Federal and state regulations requiring FW to be diverted from landfills to composting and energy generation facilities have recently been enacted to mitigate the negative impacts of landfilling FW. For example, the state of Massachusetts has recently enacted legislation that bans landfilling of commercial organic/food wastes for entities that produce over one ton of FW per week (Massachusetts Office of Energy and Environmental Affairs 2015). California Assembly Bill (AB) 1826 was introduced for source-separation and recycling of organic waste intended to reduce GHG emissions. The bill requires businesses producing over four cubic yards of organic waste per week to recycle those wastes (California Department of Resources Recycling and Recovery 2015). This bill may extend to include businesses producing over two cubic yards of organic waste if the state does not meet its goal of 50 percent organic disposal reduction by 2020.

Environmental, economic, and regulatory drivers are encouraging businesses and municipalities to explore the codigestion of FW. However, widespread implementation has yet to be realized due to multiple technological barriers and knowledge gaps that still exist. This project focuses on a) improving food waste collection and handling (via preprocessing), as well as b) implementing a codigestion strategy that advances biogas generation and downstream biosolids processing. The goal of these two steps is to encourage the diversion of food waste from landfills, and to recover lost digester gas as an alternative and renewable energy source

An additional indirect benefit of this project is the acquired insight and experience for the design and operation of FW digestion facilities. Figure 1 summarizes the key barriers for adopting codigestion technology at existing WWTPs.

Figure 1: Key Barriers to Integration of Codigestion With Existing WWTP Facilities



Concerns in the order of increasing importance for the integration of codigestion from literature.

Source: Modified and recreated from (Nghiem, Koch, et al., 2017)

1.2 Food Waste Digestion Potential, Benefits and Current Status

While an increase in biogas production from AD can result in energy savings, the savings alone may not justify a codigestion project for many wastewater utilities, especially small-capacity facilities or larger ones requiring extensive upgrades. The lack of cost-effective separation of digestible matter from FW, and the potential increase in dewatered cake mass (which requires greater effort in disposal) pose possible barriers to adopting the codigestion strategy. This project demonstrated two complementary approaches to lower the cost of organic waste codigestion:

1. A novel technology to lower the preprocessing cost of FW: This new technology included a two-step process: Off-site preprocessing of the waste using an organic extrusion press (OEP) at the centralized waste facility and further on-site polishing using an organic polishing system (OPS) prior to digestion. In this report, the term "preprocessing" refers to contaminant removal from municipal solid waste (MSW) at the centralized waste facility; further cleaning of the preprocessed FW at the receiving WWTP is termed "polishing."
2. A new strategy to lower the mass of dewatered cake solids from codigestion: This strategy involved an analytical approach of sequentially increasing the volatile solids

(VS) contributed by co-wastes in the digester. The strategy is explained in detail in Section 3.2. Digester operation with only sludge feed established the benchmark performance (dewatering efficiency and biogas generation). Codigestion performance was studied using the addition of FOG in the second phase of testing, or preprocessed FW in the third phase of testing.

This strategic co-waste addition enhances VS destruction while potentially improving dewatering characteristics. The strategic loading is also intended to facilitate a better understanding of the "sludge/organic waste" interactions, as explained in the subsequent chapters of the report. Such a strategy helps identify which loading enhances dewatering characteristics and lowers the mass of dewatered cake solids generated. Consequently, the net mass of dewatered sludge cake, which requires disposal, and the resulting landfill tipping fees may be reduced.

The novel technology for FW preprocessing coupled with the strategic addition of organic waste to the digesters is expected to improve the overall economics of codigestion to WWTPs. This project uses a novel FW preprocessing technology that includes two process steps. Step 1 consists of OEP, commercially known as the organic extruder press (OREX), which removes large non-biodegradable materials by allowing only organic matter to be extruded. Step 2 consists of an on-site OPS that removes finer inert material from the OEP-extracted FW located at the project site, Silicon Valley Clean Water (SVCW) WWTP. The two combined steps can enhance organics recovery compared to other FW preprocessing technologies currently in use. This FW preprocessing technology eliminates the need for manual source separation of FW sources and removes large unwanted non-biodegradable material (such as metals, plastics, and paper) and finer particles (inert materials) from digestible organic materials to make them suitable for addition to the digesters.

1.3 Goal and Objectives

The overall goals of this study are to encourage the diversion of food waste from landfills, to recover digester gas as an alternative and renewable energy source and to demonstrate economic feasibility of FW preprocessing and codigestion. This is achieved by two complementary approaches, namely, a new strategy to lower the mass of the cake solids requiring disposal during the codigestion process and a new technology to lower preprocessing cost of food waste.

The specific project goals were to demonstrate:

1. FW can be reliably and cost-effectively preprocessed by the OEP and OPS units. The goal is to demonstrate a reduction of 10 percent in preprocessing cost.
2. Preprocessed FW can be handled and fed to the digesters with minimal attention by the demonstration site staff.
3. Gas production increases by approximately 70 percent.
4. Cake solids produced by the dewatering process corresponds to the strategic loading of co-wastes (such as FOG and FW) and decreases by approximately 5 percent (on a "total solids" normalized basis) by adding food waste.

The specific project activities established to achieve and quantify these goals include:

- Benchmark digester operations and digested solids characteristics prior to adding organic cowastes.
- Perform codigestion studies with varying FOG loading ratios to obtain biogas generation and digested solids dewatering data.
- Characterize preprocessing efficacy by the OEP and OPS to sort organic waste from collected FW.
- Perform codigestion studies with varying FW loading ratios to obtain biogas generation and digested solids dewatering data.
- Measure and validate power consumption of the OREX press and all the on-site digester and dewatering equipment components at SVCW.
- Conduct detailed economic and non-economic benefits evaluation for the studied codigestion strategies.

1.4 Report Scope

The intent of this report is to present data that clearly demonstrates the economic, environmental, and regulatory advantages of implementing FW codigestion by other wastewater utilities. The project shows full-scale data and pertinent information to overcome barriers to achieving California's statutory energy goals. This is achieved by demonstrating a novel technology for preprocessing FW combined with an operational strategy for codigestion of WWTP sludge and organic wastes that can prove to be economically viable for utilities.

The report potentially could provide guidance to estimate codigestion loadings, energy production, food waste preprocessing efficiency, sludge reduction, preprocessing and codigestion cost estimates and GHG emissions reductions to help utilities evaluate site-specific projects.

1.5 Report Organization

The remainder of the report includes the following chapters:

- Chapter 2 provides a technology review summarizing available information on FW preprocessing technologies. The influence of codigestion operations on gas production and solids dewatering is also discussed.
- Chapter 3 provides a discussion of the overall project approach, description of the demonstration facilities, and the methods used to obtain data and document the process results.
- Chapter 4 presents the results of benchmarking studies without co-waste addition.
- Chapter 5 details the FOG codigestion study and comparison of the results between the benchmarking and FOG tests.
- Chapter 6 details the FW codigestion study and comparison of the results between the benchmarking, FOG, and FW tests.
- Chapter 7 provides an evaluation of the projected benefits of the codigestion.
- Chapter 8 provides an outline and summary of the measurement and validation (M&V) analysis.

- Chapter 9 provides the production readiness plan.
- Chapter 10 presents a summary and conclusions of the study.
- Appendix A (results from the M&V by Base Energy) and Appendix B (technology transfer efforts to date through conference presentations and abstracts), available under separate cover (Publication Number CEC-500-2020-XXX-APA-B).

CHAPTER 2:
Literature and Technology Review

This chapter provides a review of the preprocessing methods and technologies used for sorting food waste (FW) and a literature review on the codigestion strategy. The effects of codigestion operations on gas production, digester chemistry, and solids reduction are included in the discussion.

Some of the literature review discussed in this section was adapted from the project team's prior work, a Water Environment & Reuse Foundation (WE&RF) report entitled "Understanding the Impacts of Codigestion: Digester Chemistry, Gas Production, Dewaterability, Solids Production, Cake Quality, and Economics" (Higgins and Rajagopalan 2017). Some data from this study has also been used to interpret and compare codigestion results in the following chapters.

2.1 Food Waste Sources, Collection, Separation, and Use

Municipal solid waste (MSW) consists of non-biodegradable material such as metal, paper, plastic, and cardboard, as well as digestible organic matter that can be diverted to anaerobic treatment. The organic material of this waste stream is categorized as organic fraction of municipal solid waste (OFMSW) and can include yard/garden waste or kitchen/FW. Waste stream composition varies depending on its origin, geographical location, local activities, habits, products available, and other factors. Waste from several different sources are characterized in Table 1 by total solids (TS), volatile solids (VS), and carbon to nitrogen ratio (C/N).

Table 1: Composition of Various Types of Waste for Codigestion

FW Type and Origin	TS (%)	VS (%)	C/N Ratio
OFMSW in Sweden		91	18
OFMSW in Denmark	41	84	
FW	17	15	11
Kitchen waste	24	23	15
Fat, oil, and grease (FOG)	1.3–3.2	86–94	22

Source: Adapted from (Morales-Polo, Cledera-Castro, et al., 2018)

Table 1 shows that waste quality (indicated by the TS and VS percentages) as well as the composition (indicated by the C/N ratio) tend to vary widely given the difference in the sources and geographical area.

FW can be generated from the entire food supply chain, including the production, processing, distribution, storage, sale, preparation, cooking, and serving of food (Xu, Li, et al. 2018). The pre-consumer FW stream (generated during production) has been well used, with a disposal rate of only 4 to 5 percent (Food Waste Reduction Alliance 2016; U.S. EPA 2012). Post-consumer FW is generated by the end user, such as restaurants, food and beverage shops, homes, and commercial cafeterias. This waste stream has shown to have the highest disposal rates, with only 37 to 42 percent being diverted to a higher value than landfill or incineration. Due to various reasons such as health and safety issues associated with source separation, poor traceability, and accountability, the diversion rate of restaurant FW was reported to be only 15 to 17 percent (Food Waste Reduction Alliance 2016; Xu, Li, et al. 2018). Collection and source separation of waste streams from these institutions is a big challenge. Typically, additional preprocessing steps are required to make the OFMSW amenable to anaerobic digestion as a way to divert digestible FW from landfills and to obtain a higher energy recovery (Xu, Li, et al. 2018).

2.1.1 Current Source-Separation of Solid Wastes, Limitations, and Implications

Collection strategy is an important factor in achieving economical FW preprocessing (Trzcinski and Stuckey 2018). Different collection strategies lead to organic streams that vary in terms of characteristics, with changing levels of impurities and organic content. The OFMSW can be either separately collected (SC-OFMSW), source separated (SS-OFMSW), or mechanically sorted (MS-OFMSW). SC-OFMSW is sourced from different waste streams that are collected separately (fruit/vegetables waste from grocery stores/markets). SS-OFMSW is the most basic pretreatment method and involves manually segregating organic materials from other waste at the establishments producing the waste (restaurants, food distributors, households, and others). MS-OFMSW can involve numerous steps (disc screen, rotating trommel screen, bag breakers, and other steps) or some high-energy pretreatments (for example, magnetic separator, crusher, grinder, macerator, and pulper) after collection. The use of mechanical methods combined with manual sorting is also popularly used.

Figure 2 shows an example of unsorted MSW from a grocery store and OFMSW that was source separated. The typical characteristics of the waste collected using the various strategies are listed in Table 2.

Figure 2: (A) MSW From Grocery Store and (B) OFMSW From Source Separation

Source: Task 4D Food Waste to Energy, EMWD Energy Management Plan, Kennedy Jenks Consultants, 2014.

Table 2: Typical Characteristics of SC-OFMSW, SS-OFMSW, and MS-OFMSW

Type of Separated Waste	TS (%)	VS (%)	COD/VS Ratio
SC-OFMSW	5–13	78–92	0.7–1.5
SS-OFMSW	12–24	91–92	0.9–1.1
MS-OFMSW	51–95	29–57	0.8–1.6

TS: Total Solids; VS: Volatile Solids; COD: Chemical Oxygen Demand

Source: Adapted from Trzcinski and Stuckley, 2018

Table 2 shows that the source separated (SS-OFMSW) and the separately collected (SC-OFMSW) materials typically have a higher VS concentration, indicating that these sources have a higher digestion potential. However, SC-OFMSW can be difficult to implement if the collection protocol and infrastructure are not already in place. Typically, separate waste collection costs are 1.5 to 3 times higher than collecting MSW for waste processing facilities. Separate collection is also susceptible to high contamination (up to 25 percent). SS-OFMSW produces a cleaner waste that can be more readily processed at the receiving WWTPs prior to digestion, but there are several limitations associated with this practice, including:

- Education and training of staff at solid waste generating facilities
- Availability and limited space for separate containers
- Higher costs of labor-intensive source separation activities
- Low organic material recovery and contamination from inorganic material due to ineffective manual separation
- Potential health effects due to exposure and handling of wet putrescible, odor-producing wastes in solid waste generating or sorting facilities

As a result, there is significant resistance and low participation from solid waste producing facilities to provide source-separated organic wastes.

In the past decades, unseparated MSW has been mechanically treated to separate the organic fractions for codigestion. Such a strategy not only yielded low biogas production (approximately 2200 cubic feet per ton), but also created several equipment and operational issues at the receiving facilities (Bolzonella, Battistoni, et al. 2006). Reports of such failures with various types of anaerobic digesters all treating MS-OFMSW have been published over the past few decades (Cecchi and Bolzonella 2005; Edelmann and Engeli 2005; Macé, Dosta, et al. 2005; Trzcinski and Stuckey 2018).

Therefore, regardless of the collection and sorting strategy, additional preprocessing steps are required to completely remove inert material and contamination to produce an effective FW stream for AD.

2.1.2 Present Preprocessing Practices

Source-separation or mechanical separation of OFMSW is usually carried out in centralized waste processing facilities. After source-separation, separate collection, or mechanical separation of OFMSW, additional preprocessing is required to remove remaining non-biodegradable materials such as utensils, plastic bags, and straws, before an organic stream can be derived for energy recovery. Bag breakers or low-speed high-torque machines are first used to open bagged wastes and release trapped organic matter. Depending on the nature of waste stream, the impurities present, and the preprocessing method applied, additional polishing steps may need to be implemented at the receiving WWTP (discussed in Section 2.1.2.3). If not removed, these materials can potentially clog mechanical equipment. Ineffective separation can also result in accumulation of these materials in the digesters, which reduce the available digester volume, increase maintenance requirements, and increase digester cleaning frequency.

A brief description of some of these preprocessing and polishing technologies are provided in the following sections.

2.1.2.1 Centralized Preprocessing Systems

More advanced FW processing solutions consist of a series of preprocessing steps for converting FW to valuable biomass within a single system. These systems produce a final product that is ready for AD at WWTPs without requiring additional raw materials or polishing steps. Some systems integrate mechanical sorting and particle size reduction and produce a bio-slurry product. The most widely known of these systems in the United States is the proprietary CORe® process, a centralized organics recycling system that produces an engineered bioslurry (EBS®) with a solids content ranging between 14 to 18 percent (HDR, Inc. 2017). This bioslurry does not require any polishing steps at the WWTP because all preprocessing steps occur off-site at the waste processing facility. Processes such as the Ros Roca Process use a turbo mixing system that produces a suspension at 15 percent TS and separates out stones, glass, and other materials by a grit settler system. The suspension produced in the first step is further treated via a screen, an aeration sand trap, and a crushing unit that reduces the size to below 12 millimeters (mm). The product is then batch pasteurized in a mixing tank, ensuring a high quality waste product (Seldal 2014). In such cases, the FW quality standards are already monitored prior to product delivery into the WWTP. This enables feed of the slurry into the digester with minimal operational staff to support the operations, as well as lesser maintenance requirements on the receiving facilities and digestion equipment due to good product quality. However, these processes need a good quality source-separated MSW stream, which requires extensive manual and mechanical separation prior to the pretreatment, which would involve higher sorting costs. Thus, equipment that can process MSWs of varying quality is necessary.

In North America, there has been a recent increase in adopting digestion of the preprocessed FW at the centralized waste processing facility itself. Such centralized waste processing systems include a digestion method specifically suited for the pretreated waste (dry/ high rate digestion, and so forth) following the preprocessing steps. Some of the available combined technologies include: the Biotechnische Abfallverwertung (BTA, biotechnical waste processing) technique employs a two-stage system using a waste pulper that separates a wet waste mixture into fractions based on their buoyancy, with the digestible light fraction kept and the suspension containing sand and other grit sent to a disposal system (Bozano Gandolfi, Nosiglia, et al. 2012). The central part of the BTA process is the pulper, where the pre-shredded feedstock is diluted to 8 to 10 percent TS (maximum 12 percent TS) and then chopped. Feedstocks such as OFMSW alone or in combination with industrial waste, sewage, or agricultural waste can be treated and used in the BTA fermenters with special mixing technology. BioSep is another FW separation technology similar to the BTA process, but with an additional third step that uses a hydrocyclone to remove sediments smaller than 10 mm (Seldal 2014). These two processes are popular in Europe. These systems seem to be less constrained by the quality of the source MSW, and a highly sorted stream does not seem to be necessary. The other advantage of such a combined large-scale preprocessing and digestion system is the elimination of the need for transporting the preprocessed FW to the WWTPs. But these facilities have to be large to derive any benefits due to economies of scale. For this reason, existing combined preprocessing and digestion facilities are mostly in the range of 100 to 300 tons per day (TPD) in the United States (HDR, Inc. 2017). High infrastructure costs of these combined systems, coupled with excess digestion capacity in WWTPs, make codigestion in the latter a widespread option.

Based on the preprocessing systems discussed so far, source MSW quality and associated source separation costs seem to be major constraints in selection of a preprocessing technology. Centralized waste facilities need preprocessing equipment that can process large quantities of MSW streams of different purity. It is for this reason that waste separation presses have gained popularity (HDR, Inc. 2017). The extract produced by the presses has been shown to be easily polished at the WWTP in various studies (Gray, Suto, et al. 2007; Gray, Suto, et al. 2008; HDR, Inc. 2017). Different types of presses are discussed in the following sub-section.

2.1.2.2 Waste Separation Presses

These presses help mitigate the disadvantages of the other preprocessing systems that require high energy, enable less control of the product quality, and require extensive manual separation prior to the process. Presses can be also successfully implemented where the co-mingled waste has a high organic content and the digestion process requires a lower TS feed stock. Several of these presses are in operation at full-scale facilities in Europe. They process a variety of feedstocks, the most common being MSW. The following are some of the commercially available press systems:

- Dupps Company Depackaging System (Dupps Company 2016): This system contains shredders with internal swing-hammers designed for material size reduction and initial separation of nonorganic material from organic material. This is followed by a screw press from which organic material, or “pressate,” is released as a viscous material ready for anaerobic digestion.
- DODA USA Bio Separator (HDR, Inc. 2017): This system consists of high-speed recirculating pumps that help separate packing material and remove inorganics. FW-bearing slurry is pumped from the vault into a screen-type bio separator, where light plastics and debris are removed. Slurry is pumped to a hauler for transit.
- Scotts Equipment Turbo Separator: This system uses conveyors to carry material into the turbo separator, where a rotating shaft with paddles opens packaging, separates organics from packaging, and conveys packaging out of the machine. Recovered organics are collected in a hopper.
- Ecrusor Depackaging and Grinding System: In this system, packaging is broken apart by spiral grinding screws that agitate and squeeze out organic material as they move. The system also consists of chopping/cutting teeth that break up the material to a size

larger than a perforated plate screen thus keeping the inert material in. The final product is a pureed organic material that can be digested.

- Organic Extraction Press (OREX/OEP) (Anaergia 2016; HDR, Inc. 2017): OREX operates on the principle that soluble organic matter behaves like a liquid under the high compression pressure. These organics are separated from the non-organic fraction in the form of an extruded product. The produced organic stream has low fiber and contaminant levels. The organic product (a total solids content between 25 and 35 percent) can then be hauled and transported and is already broken up, aiding in digester gas production and energy conversion.

2.1.2.3 Polishing Trains at Wastewater Treatment Plants

Commonly employed polishing techniques use physical processes including grinders, mincers, screw presses, paddle finishers, disc screen shredders, and piston presses to separate inorganic contaminants from the organics (Ariunbaatar, Panico, et al. 2014; HDR, Inc. 2017; Morales-Polo, Cledera-Castro, et al. 2018). Mechanical screening, such as disc screens or rotating trommel screens, can be used at multiple stages along the process train to separate smaller materials (less than two to four inches in diameter). These mechanical and physical pretreatments not only separate the large and unwanted materials from the waste, but also reduce particle size. The increased surface area for contact allows for a better interaction between the waste and microorganisms during digestion. In various cases in literature, biogas yields improved between 9 and 34 percent when source-separated FW was ground prior to digestion (Morales-Polo, Cledera-Castro, et al. 2018). A comparison of various common preprocessing/polishing methods and their effect on codigestion performance in the literature is presented in Table 3.

Table 3: Comparison of Different Preprocessing Methods to Enhance Codigestion of Food and Similar Wastes

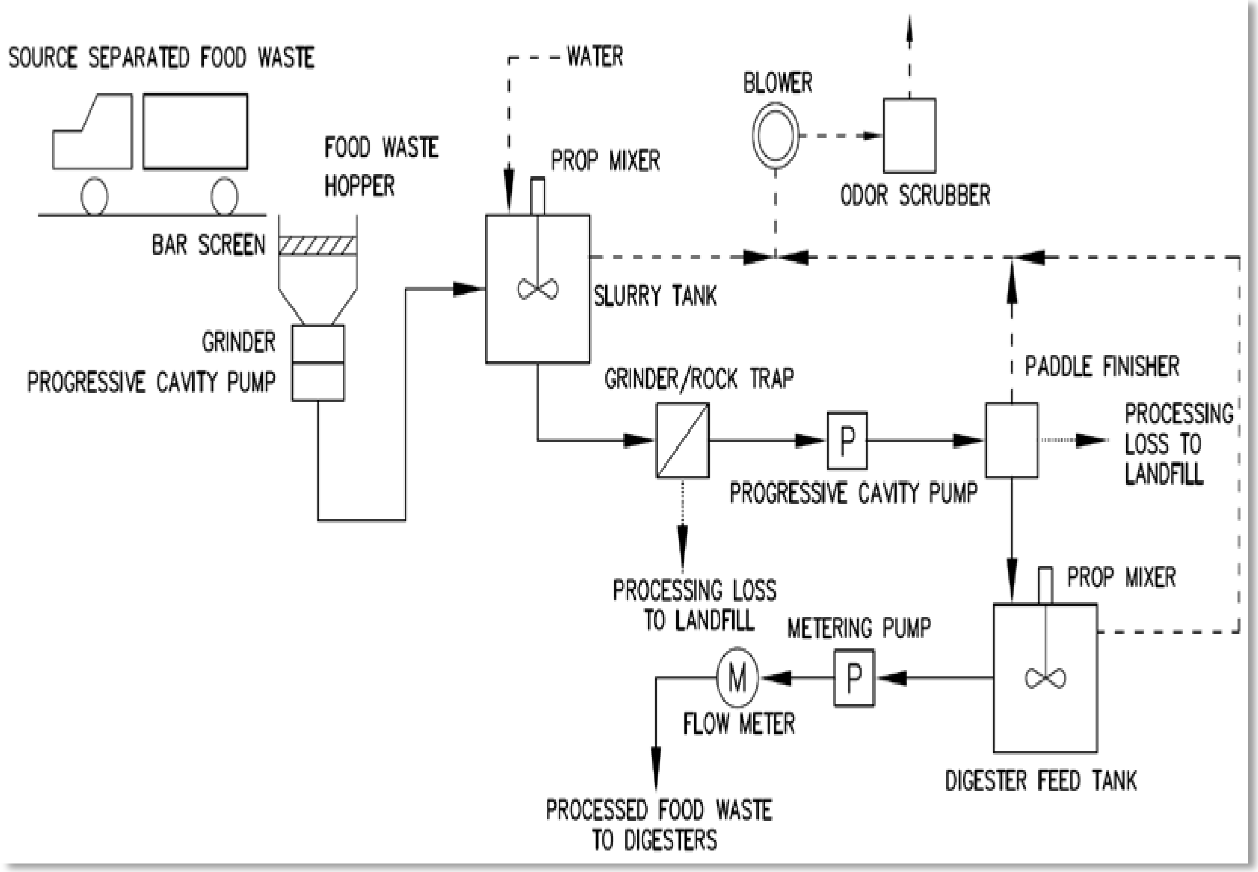
Type of Waste	Preprocessing/Polishing Type	Results/Observations
OFMSW (source-sorted)	Disc screen	81% VS reduction with 5.41 cu.ft. CH_4/lb VS
OFMSW (source-sorted)	Screw press	63% VS reduction with 5.67 cu.ft. CH_4/lb VS
OFMSW (source-sorted)	Shredder with magnetic separation	63% VS reduction with 4.63 cu.ft. CH_4/lb VS
FW	Size reduction by beads mill	40% higher COD solubilization
FW	Screw press, disc screen, shredder with magnet	Shredder with magnet assembly produced highest methane yield of 1.79 cu.ft. CH_4/lb VS; Screw press and disc screen produced lower yields at 0.64–0.96 cu.ft. CH_4/lb VS waste
FW	Bead mill, food waste disposer	Decreased methane production
FW and dairy manure	Grinding	Reduction in particle size from 2.5 to 8 mm increased methane production rate by 10–29% as well as methane yield by 9–34 %
OFMSW	Screw press and screening	Biogas yield increased by 15%
FW	Grinding	Size reduction of 2.5–8 mm yielded a CH_4 increase between 9–34%
FW	Milling	Excessive size reduction and overloading. Process imbalance due to VFA accumulation.
FW	Pressure (10 bar) + Depressure (1 bar)	Biogas production increased by 35%
FW + sludge	Size reduction	Biogas yield increased by 10–25%

CH_4: Methane; VFA: Volatile Fatty Acids

Source: Adapted from (Ariunbaatar, Panico, et al. 2014; Chiu and Lo 2016; Morales-Polo, Cledera-Castro, et al. 2018)

A schematic of the typical polishing steps used for source separation of organic wastes is shown in Figure 3.

Figure 3: Typical Preprocessing System for Source-Separated Organic Wastes



Source: Task 4D Food Waste to Energy, EMWD Energy Management Plan, Kennedy/Jenks Consultants, 2014.

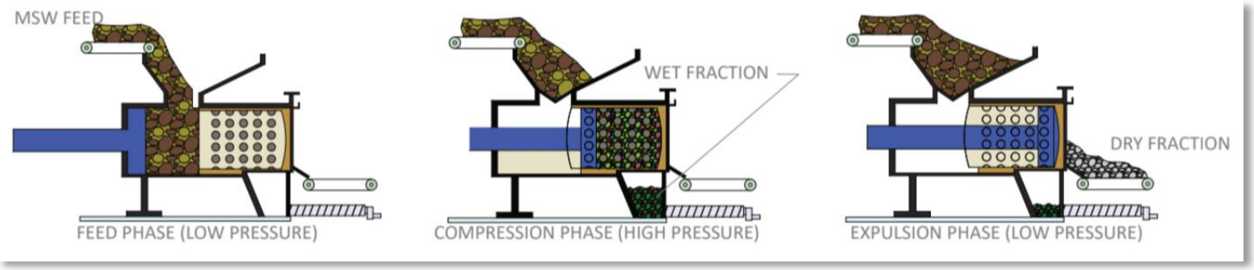
2.1.3 Preprocessing Technology for This Demonstration

Of the various technologies discussed in the previous section, the technology selected for this demonstration study is a press preprocessing system consisting of the OREX press, followed by an organic polishing system (OPS). The OREX press was selected due to its proximity to the test site at SVCW for ease of FW delivery. Prior demonstrated polishing and codigestion of OREX waste and the ability of the press to process commingled waste were added reasons for its selection.

2.1.3.1 Organic Extrusion Press

The organic extrusion press technology (OEP/OREX) is developed by Anaergia Services (Carlsbad, Calif.). The OREX/OEP technology separates the incoming waste into organic (wet) and inorganic (dry) fractions through the application of pressure on the order of approximately 4000 pounds per square inch (psi). Figure 4 depicts how the OREX processing unit treats the mixed solid waste stream.

Figure 4: OREX Processing Line for Physically Separating Mixed Solid Waste



Source: (Anaergia, 2019)

Mixed solid waste is fed to a perforated chamber where it is compressed under high pressure. This pressure liquefies and squeezes the relatively more viscous organics (wet fraction) down, while paper, plastic, and other materials (dry fraction) are removed. The pressed organic "unders" collect in a chamber below the press for recovery. Pressed and dried "overs" are ejected from the chamber for recycling or disposal. The OREX press has been reported to recover up to 95 percent of digestible organics (Anaergia 2016). Other FW preprocessing technologies that focus solely on size classification only recover between 25 percent to 65 percent of digestible materials. Table 4 summarizes the performance of the OREX press at a field demonstration at San Carlos, Calif.

Table 4: Performance Summary of OREX/OEP Field Demonstration

Biogas Production (cu.ft./lb VS)	Methane Content (cu.ft./lb VS)	Inert Material in Wet Fraction	Organic Materials in Dry fraction	Heavy Metals
10.72	7.59	78% to 92%	2% to 5%	Below EPA Limits

Samples not processed through OPS unit.

Source: Communication from Anaergia, 2013.

The field demonstration study at San Carlos, Calif. (Table 4) showed that the amount of organic material in the dry fraction was between 2 and 5 percent. This demonstrated that an effective separation of organic materials is achievable by the OREX press. The extruder allows only small materials in the pressed product and prevents bigger contaminants from reaching the receiving facilities (for example, glass bottles, cutlery, and other contaminants). This enables smooth operation and reduces maintenance downtime for the FW-receiving WWTPs. Additionally, OREX produced a high energy density product without significant contaminants. The generated biogas and methane content of the San Carlos demonstration study were comparable to digestion of municipal sludge. Typical values for municipal sludge are 11.85 cubic feet per pound VS (for biogas) and 8.65 cu.ft./lb VS (for methane).

In addition to the high separation efficiency, OREX operation also avoids the potential health effects associated with traditional source separation. This technology has been successfully installed and operated in multiple WWTPs throughout Europe, with processing load sizes ranging from 20,000 to 200,000 tons per year (tpy). Field data have consistently shown that OREX extracts more than 95 percent of the organic materials. Table 5 presents a list of all OREX installations described in the literature.

Table 5: OREX Installations Around the World

Description of OREX Treatment	Country	Capacity (tpy)	Year
Sorting and treatment of mixed MSW	Kaiserslautern (Germany)	50,000	2006
Sorting and treatment of mixed MSW	Alessandria (Italy)	100,000	2007
Treatment of bio-waste (separately collected)	Castelceriolo (Italy)	25,000	2008
Treatment of bio-waste (separately collected)	Viareggio (Italy)	20,000	2008
Sorting and treatment of mixed MSW/ industrial waste	Premier Waste (UK)	100,000	2008
Treatment of mixed MSW	VamWijster (Netherlands)	200,000	last changes 2009
Vagron (MBT) anaerobic digestion of organic fraction from MSW	Groningen (Netherland)	100,000	last changes 2009
Sorting and treatment of mixed MSW	San Francisco (USA)	15–20 tons/hr	2016

Source: (Anaergia, 2016)

2.1.3.2 Organic Polishing System

The organic polishing system (OPS) is a plastic film and other light debris removal system, consisting of a paddle finisher. This system removes fine non-digestible materials in the organic fraction extracted by the OREX press and produces a FW slurry that can be fed to the digesters. The paddle finisher has two to four paddles of different pitch and one heavy duty cylindrical or helical perforated screen. Different ranges of size openings in the screen can be selected based on the application. These paddles rotate along the inside length of the screen (Gray, Suto, et al. 2008). The soft, organic material is pushed and extruded through the screen, using a water spray to ease movement of material. The polished solids are in the form of a pulp that is transferred into the FW storage tank and then into the digesters. The bigger materials, which are not extruded through the screen openings, are moved by the paddles down the inside length of the screen and conveyed out of the finisher. This waste is trucked out along with the trash. Table 6 lists some of the full-scale facilities using the polisher or other methods for processing FW on site prior to digestion.

Table 6: Summary of Full-Scale Food Waste Polishing Methods in Use

	CMSA	EBMUD	Hill Canyon	Sheboygan	West Lafayette	Janesville
Digester Conditions	Mesophilic	Thermo-phillic	Mesophilic	Mesophilic	Mesophilic	Mesophilic
Hauler Preprocessing	Sorts & grinds into 1-inch solids	Remove large objects & metals grind into ~2-inch solids	Cleaned for contaminants then chopped and mixed.	Screen at unloading	FW separated & ground	
On-site Polishing	Grinder & paddle finisher	Grinder & Paddle finisher	Fed through manually raked bar screen before entering digester		FW grinder FOG heavy object trap	Mechanical bar screen
Feed Rate (GPM)*	30	550	10-20	35-55	30	25
Percent Total Solids**	10	35	5 (FOG)	3	~20	4.5

***Gallons per Minute (GPM)**

****Varies greatly with the source material.**

Source: (Ely, C. S. and Rock, 2014)

2.2 Food Waste Codigestion Strategy

While codigestion enhances biogas production, the effect of codigestion on stable digestion operation and downstream processes, such as dewatering and solids disposal, is of concern to utilities. The project team's prior research has shown that utilities can operate codigestion in innovative ways that maximize the process benefits (Higgins and Rajagopalan 2017). For example, by selecting the right co-waste and suitable loading, it is possible to optimize benefits such as gas production and cake solid reduction and minimize unwanted side effects such as ammonia inhibition or foaming issues in digester.

Proper management of codigestion includes balancing the following factors:

- Increasing biogas (methane) production and volatile solids reduction
- Maintaining proper digester chemistry

- Providing adequate mixing to control foaming potential
- Improving digested solids dewatering (cake solid reduction)
- Controlling cake odors

Each of these factors is discussed in more detail in the following sections.

2.2.1 Increasing Biogas (Methane) Production and Volatile Solids Reduction

Multiple studies have shown that the codigestion of FOG, OMFSW, or FW with municipal sludge can significantly increase biogas production (Higgins, Rajagopalan, et al. 2016; Mata-Alvarez, Dosta, et al. 2014; Mata-Alvarez, Dosta, et al. 2011). Studies investigating codigestion of various FOG wastes have demonstrated biogas production to increase anywhere from 10 to 200 percent (Davidsson, Lövstedt, et al. 2008; Ely, C. S. and Rock 2014; Kabouris, Tezel, et al. 2009; Luostarinen, Luste, et al. 2009; Wan, Zhou, et al. 2011). Municipal sludge is compatible for FW codigestion due to its high alkalinity and trace elements content (Higgins et al. 2016). The optimal mixing ratio of FW and sludge vary significantly in published literature, but the most common range of FW addition was 33.3 to 50 percent (weight/weight (w/w) total feed solids) (Kuo-Dahab, Amirhor, et al. 2014; Prabhu and Mutnuri 2016; Xu, Li, et al. 2018).

In cases where OFMSW is added as an organic waste to a sludge digester, Zupančič et al. reported an 80 percent increase in biogas production (Zupančič, Uranjek-Ževart, et al. 2008). In another study, SC-OFMSW was fed after size reduction, at an amount that increased the total digester loading by 20 percent. This resulted in a 25 percent increase in biogas production (Edelmann, Engeli, et al. 2000). Fruit and vegetable waste that were not preprocessed were added to two full-scale digesters in series and resulted in an increase in biogas production of 8 to 17 percent (Park, Thring, et al. 2011)

The effectiveness of FW in increasing biogas production differs based on the type of FW as well as the preprocessing method being used. The limitations associated with poorly digestible FW can be overcome by blending compatible waste in an optimal ratio that enhances digestion and gas yield, mainly due to synergistic effects.

Synergistic effects are defined as a phenomenon where codigestion of substrates with sludge results in better performance than when the substrates are digested separately (Aichinger, Wadhawan, et al. 2015; Labatut, Angenent, et al. 2011; Zhang, Zhang, et al. 2015). The effect of FW loading rates on digester methane production were illustrated by Higgins and Rajagopalan (2017). The control digester reactor produced 3.3 liters per day of methane, while adding 24 percent to 58 percent of FW increased methane production to 4.9 to 7.0 liters per day. The predicted (modeled) volatile solids reduction increased with greater FW loading and then decreased, suggesting that the maximum synergistic effect occurred at a loading rate of 38 percent additional volatile solids.

Table 7 lists various types of FW/OFMSW preprocessing and codigestion systems previously studied. The digester VS loadings and corresponding unit gas production are listed for each case. While results are highly variable due to the scale, digestion type, and feedstock used in each case, the results indicate that higher VS or chemical oxygen demand (COD) removal is achieved with codigestion compared to digestion of sludge only.

Table 7: Summary of Codigestion from Literature Sources for FW and OMFSW

Codigested Feedstock	Process Configuration/ Type	Influent TS (%)	VS Loading Rate (g VS or COD/L day)	SGP (cu.ft. biogas/ lb VS)	CH_4 (%)	VS or COD Removal (%)
MSW	Thermophilic	14.3	12.9	5.92	58	76.2
OFMSW	Thermophilic	23–30	6–7	12.8–14.4	50	98
FYV	Shredding followed by Thermophilic dry digestion	F:40	11.1	5.21	62	—
MS-OFMSW	Valorga, Mesophilic	30	5–13.7	3.36–4.81 (CH_4/g VS)	—	50–70
SS-OFMSW	Kompogas, Thermophilic	30	—	3.36–4.81 (CH_4/g VS)	—	50–70
MSW	Dranco, Thermophilic	31–57	12–15	4.00	72–80	80

Abbreviations: F =feed; FV = fruits and vegetables; FW = food waste; FYV = fruit, yard, and vegetable waste; MS-OFMSW = mechanically sorted organic fraction of municipal solid waste; SGP = specific gas production.

Source: (Morales-Polo, Cledera-Castro, et al. 2018)

2.2.2 Maintaining Proper Digester Chemistry

Addition of organic co-wastes to digesters alters the digester environment (for example, volatile solids loading, carbon to nitrogen ratio, pH), which can lead to changes in digested solids' characteristics. Understanding the interactions between organic wastes and sludge and the effect of these interactions on digester chemistry can help to improve digester performance and prevent process upsets (Muller, Gough, et al. 2009). The relationship between codigestion and digester chemistry is discussed in the following sections.

2.2.2.1 pH, Alkalinity, and Volatile Fatty Acid Balance

pH is an important factor in the performance and the stability of an anaerobic digester. The pH required for stable anaerobic digestion is between 6.5 and 7.6 (Hills, 1979) and should be maintained at a pH above 6.8 to provide a buffer for fluctuations in operation. Failing to maintain the pH within an appropriate range can cause reactor failure (Franke-Whittle, Walter, et al. 2014). The main cause of low pH is an accumulation of volatile fatty acids (VFAs) due to an imbalance in their formation and consumption during digestion.

VFA accumulation occurs when there is an imbalance in the steps occurring in anaerobic digestion. The initial step in the anaerobic digestion is the hydrolysis of the organic materials during which proteins, carbohydrates, and fats are broken down to amino acids, sugars, and fatty acids, respectively, by bacteria (Lee, Lee, et al. 2015). In the second step, acidogenic bacteria convert sugars, amino acids, and fatty acids to organic acids, acetate, carbon dioxide (CO_2), and hydrogen (H_2). Acetogenic bacteria then convert organic fatty acids and alcohols into acetate, hydrogen, and carbon dioxide, which are used by methanogens to form biogas in the last step, called methanogenesis (Higgins and Rajagopalan 2017). Effective and efficient anaerobic digestion relies on the continuous conversion of intermediates produced in the metabolic chain. An imbalance between acid produced and its consumption by the methanogens can lead to a pH decrease and digester failure. Some co-wastes may not cause this type of failure, but could cause a depletion of alkalinity, resulting in a low pH at steady-state conditions due its chemical composition. For instance, co-wastes with low or no nitrogen, like glycerol or FOG, may cause a digester to operate at low pH and alkalinity resulting in unstable operations.

The buffering capacity of an anaerobic digester is determined by the amount of alkalinity present in the system, from both the influent sludge and that produced within the digester. Alkalinity is contributed by both the effect of effect of the carbon dioxide/bicarbonate and ammonia/ammonium. Well-operated digesters are considered to be sufficiently buffered due to the effect these two sources of alkalinity.

In codigestion very high levels of acetic acid have been reported (Moeller et al. 2010). But it is difficult to explain if high VFAs in the digester are the reason for or a consequence of the imbalance in the process (Ganidi et al. 2009). Different reasons for the pH imbalances may take place, but foaming has been reported due to lower pH that resulted from the production of VFA or feed imbalances (Labatut et al. 2011; Ganidi, Tyrrel, et al. 2009).

Overloading and inhibition are the main causes of VFA accumulation and acidification in digesters. In these cases, the rate of volatile fatty acid and hydrogen production exceeds the rate of volatile fatty acid consumption, leading to a failure. This can be prevented by introducing co-wastes waste slowly until the desired loading rate is achieved. This allows the different microbial populations time to grow, stabilize, and get acclimated so that the rates of the various digestion steps are balanced (Higgins and Rajagopalan 2017). It is for this reason that acclimation of digesters to reach steady state at every co-waste loading condition is important for good digester operation.

The potential synergistic effects of codigestion of FW were demonstrated by Higgins and Rajagopalan (2017). FW loading was increased to a digester and the pH increased from 7.4 for the control up to about 7.8 for 38 to 58 percent additional VS loading from FW (Higgins and Rajagopalan 2017).

2.2.2.2 Carbon to Nitrogen Ratio and Ammonia Inhibition

Optimal codigestion requires carefully balancing the carbon-to-nitrogen (C/N) ratio in the co-substrate mixture, as well as macro- and micronutrients, and pH in the digester (Higgins, Rajagopalan, et al. 2016). High C/N ratios can deplete the necessary nitrogen source for biomass growth; whereas, lower C/N ratios lead to the accumulation of ammonia. FW is an example of a substrate with a low C/N ratio that can have synergistic effects when fed during codigestion or reduce digester performance if fed as the sole substrate or at excessive loading rates. FW is not well digested as the sole substrate because its high protein content typically leads to elevated concentrations of ammonia or ammonium ion in the digester (Yenigün and Demirel 2013). Ammonia is the result of the degradation of nitrogenous compounds such as proteins and urea found in food and garden waste. Ammonia molecules can cause inhibition of anaerobic digestion at certain concentrations. Ammonium ion (NH_4) and free ammonia (NH_3) are the two principal forms of inorganic ammonia nitrogen in aqueous solution. The total ammonia nitrogen (TAN) is comprised of ammonia (NH_3) and ammonium (NH_4^+). Ammonia is sometimes also called "free ammonia nitrogen," or FAN, because it is "free" of a proton (Sung and Liu 2003; Yenigün and Demirel 2013).

The literature has reported a wide range of ammonia concentrations that could potentially cause inhibition. Mata-Alvarez (Mata-Alvarez et al. 2000) reported inhibition occurred at TAN greater than 1200 milligram/liter (mg/L). El Hadj et al. (2009) found that methane generation in mesophilic digestion batch tests with a high-protein synthetic biowaste decreased by 50 percent at ammonium ion concentrations of 3860 mg/L of ammonia nitrogen (NH_4-N) (Benabdallah El Hadj, Astals, et al. 2009). Although there is no consensus on the ammonia concentration that causes inhibitory effects, it is clear that nitrogen concentration and C/N ratio of the feedstock affect the digester performance and process stability. Different inhibition levels for FAN values have been reported, depending on the temperature, pH, and acclimation periods, but the FAN inhibitory levels that have been commonly accepted are 100 to 150 mg/L (Sung and Liu 2003; Yenigün and Demirel 2013). In modelling the ammonium concentrations, increasing the volatile solids loading due to FW steadily increased the ammonium ion concentration from about 1,200 mg/L for the control to about 1,400 mg/L for 58 percent increase in volatile solids loading (Higgins and Rajagopalan 2017). The ammonium concentrations for all codigestion loadings were below 3,000 mg/L nitrogen (N).

The addition of co-wastes to the digester at optimal ratios based on the C/N characteristics of the wastes can be a strategy to reduce ammonia inhibition while improving biogas production. Several examples of co-waste digestion methods that resulted in improved digester performance compared to single substrate digestion include:

- Dairy manure, chicken manure, and wheat straw together exhibited better performance than substrates digested individually, as seen by a stable pH and low concentrations of TAN and FAN at adjusted C/N ratios of 25 and 30 (Wang, Yang, et al. 2012).
- Onion waste and wastewater sludge improved digester performance with a C/N ratio of 15 (Romano and Zhang 2008).
- Olive mill effluent digested with empty fruit bunches (C/N ratio of 45) produced 12 times more methane (a 62 percent higher methane yield) compared with digestion of olive mill effluent alone (Nurliyana, H'ng, et al. 2015)

Other wastes such as fish waste, abattoir wastewater, and waste activated sludge (WAS) have also been codigested with fruit and vegetable wastes. Despite a considerable decrease in the C/N ratio from 34 to 27.6, the addition of fish wastes slightly improved the gas production yield compared with that of fruit waste alone (Bouallagui, Touhami, et al. 2005). Many reports agree that the optimal C/N ratio in methane formation is between 25 and 30 (Mata-Alvarez, Dosta, et al. 2011; Nurliyana, H'ng, et al. 2015; Wang, Yang, et al. 2012). The most significant effect is that of the presence of paper in MSW, which causes high C/N ratio, affecting the OMFSW digestion and thus making it ideal for codigestion with sludge (Gomez, Cuetos, et al. 2005).

2.2.3 Foaming Potential, Viscosity, and Mixing

The effect of co-waste digestion on the digester viscosity is critical to understanding several operational parameters, including mixing, dewatering, and foaming potential. The project team's prior research has shown that as the solids concentrations of the digester increases, the suspension becomes non-Newtonian, exhibiting shear-thinning behavior (Higgins and Rajagopalan 2017). Shear rate is a measure of mixing. As the shear rate or mixing increases, the viscosity decreases. In addition, as the solids concentration increases, the viscosity also increases as do other important suspension properties such as the yield stress.

The addition of co-wastes to anaerobic digesters could change the solids concentration in the digester. This in turn could directly affect the rheology and mixing, thus influencing expansion (also called rapid rise) due to foaming and gas holdup. Viscosity as well as foaming potential of the sludge can be influenced by the presence of filamentous cells, extra-polymeric substances (EPS), lipids, proteins, and bio-surfactants (Ganidi, Tyrrel, et al. 2009). The concentrations of these substances in the sludge as well as their interactions are complex and related to several process parameters such as composition of the substrate, pH, operation temperature, VS loading rate, hydraulic retention time (HRT), and microbial constituents (Subramanian and Pagilla 2015).

Evaluating the effects of co-waste addition on mixing and gas production rates will be essential to understanding the potential and causes for rapid rise/volume expansion and foaming events. Higgins and Rajagopalan found that high strength waste addition did not have a significant effect on the digester sludge properties, though it could vary significantly on the characteristics of the waste and digester operation (Higgins and Rajagopalan 2017). As a general rule, many rapid rise issues can be reduced by proper loading to codigestion wastes and digester operation.

2.2.4 Improving Digested Solids Dewatering

The factors that affect dewatering after anaerobic digestion are complex related to sludge-co-waste interactions. The dewaterability of biosolids is strongly dependent on the biosolids' characteristics such as the VS content (Skinner, Studer, et al. 2015), extra cellular polymeric substances, and soluble microbial products (Nghiem, Koch, et al. 2017), among other factors. Codigestion could affect the characteristics of the biosolids and dewaterability in different ways:

- Monovalent to divalent cation (M/D) ratio through a change in the cation balance (Higgins, Rajagopalan, et al. 2016).
- Biochemistry of the digestion process (Silvestre, Fernández, et al. 2015).
- Fiber content (Komatsu, Kudo, et al. 2007).

In the divalent bridging theory, divalent cations such as calcium (Ca^2+) and magnesium (Mg^2+) act as bridges between negatively charged functional groups, which helps stabilize the EPS/biofloc matrix and leads to better dewatering characteristics. Most available investigations focus on the M/D ratio in solution using the soluble concentrations as a measure of cations available for the floc formation. In general, as the M/D increases above 2, polymer demand and cake solids worsen (Higgins and Murthy 2006; Murthy and Novak 1999; Novak, Verma, et al. 2007) Higgins and Rajagopalan (2017) found that at M/D ratios between 5 and 40, the cake solids percentage decreased but at ratios above 40 the cake solids percentage does not change much (Higgins and Rajagopalan 2017). These researchers also found that the polymer demand increased rapidly up to a M/D ratio of 40 and then leveled off at higher M/D ratios. An

M/D ratio of 2 or less was determined to be optimal, although lower M/D ratios will likely provide improved floc properties (Higgins and Rajagopalan 2017).

Several studies have demonstrated the addition of certain co-wastes improved dewatering considerably. Increasing fruit and vegetable waste proportions in the feed improved the anaerobic codigestion effluent filterability (Habiba, Hassib, et al. 2009). Another high fiber substrate, rice straw waste, also improved dewaterability while codigested with sewage sludge, which was attributed to the high level of cellulose fibers in rice straw (Komatsu, Kudo, et al. 2007). In the codigestion of sewage sludge with crude glycerol (a highly biodegradable substrate), no change in dewaterability was observed between the control and codigestion digesters (Jensen, Astals, et al. 2014). However, codigested with crude glycerine resulted in poorer dewatering compared with the sewage sludge control (Silvestre, Fernández, et al. 2015).

Prior full-scale studies have shown that the codigestion of FOG with municipal sludge improved biosolids dewaterability and decreased the volume of biosolids (reduction in wet cake produced) by 33 percent, (York and Magner 2009). In addition, total polymer used for dewatering after FOG addition decreased by 11 percent (York and Magner, 2009). In a second full-scale study using whey codigestion, it was observed that, with up to 25 percent additional volatile solids (VS), there was no net increase in the amount of cake solids produced and the polymer demand decreased by 25 percent (Aichinger, Wadhawan, et al. 2015). In a third full-scale study involving codigestion of grease waste (GW) and FOG, only a slight improvement in dewaterability was reported but no quantitative details on cake solids or polymer demand were provided (Tandukar and Pavlostathis 2015). Higgins and Rajagopalan (2017), using mass balances, found that increasing the volatile solids loading rate up to 20 percent generally did not increase the net waste cake solids that would need to be hauled from wastewater treatment plants, compared with a control sludge only digester. Above 20 percent additional volatile solids loading, the wet cake solids were generally greater than the control (Higgins and Rajagopalan 2017).

2.2.5 Controlling Cake Quality

The most important compounds associated with the generation of odor are the volatile organic sulfur compounds (VOSCs) and nitrogen-based compounds (Higgins et al. 2002, 2003). Usually anaerobic digested sludges have lower volatile odor compounds than dewatered, stored sludge cake (Higgins and Murthy 2006). Type of dewatering equipment, polymer dose, cake handling, transport and storage can affect VOSC concentrations after dewatering (Higgins et al. 2006). Dewatering methods that break up the floc more, release more EPS-bound protein and increase VOSC concentrations. Increased polymer dose also leads to more VOSC due to more available protein in the sludge cake (Higgins and Murthy 2006). M/D ratio was found not to have a correlation with odor generation in centrifuged biosolids (Murthy and Novak 1999).

Odor production from biosolids is a complex process. A previously published study by the project team examined the effect of codigestion on cake odors. The cake odor production was higher at a lower loading rate of FW, but as the loading rate increased, the cake odor decreased to much lower levels compared to a control digester with no FW addition (Higgins and Rajagopalan 2017). The production of odorants by cake solids was generally lower in digesters practicing codigestion where high strength wastes were added (Higgins and Rajagopalan 2017).

2.3 Summary

Codigestion of alternative feedstocks (FW and FOG) with sludge is a way to increase biogas production and energy recovery at WWTPs. Preprocessing of FW prior to anaerobic digestion can reduce undesirable effects on the receiving equipment and digester operation. Preprocessing can be achieved by a variety of methods to improve the quality and suitability of FW for codigestion.

Few studies reported in the literature have examined a holistic full-scale effect of codigestion for FW or FOG. However, previous pilot or lab-scale studies have shown that codigestion with various feedstocks can yield synergistic effects or cause potential problems for downstream biosolids processing. Codigestion can affect the operating AD chemistry and pH, possibly leading to digester failure, while it can also improve dewaterability of biosolids after codigestion. Cake odor production after codigestion and rapid rise foaming also pose potential problems. The cation ratio of the digestion process and the C/N ratio of the feedstock have been indicated as key parameters in controlling these issues. Investigating the type of co-waste prior to codigestion can help improve operations. Suitable preprocessing of FW, controlling its quality and loading, offers a good codigestion strategy for improving solids handling, controlling the AD treatment, and downstream processes.

CHAPTER 3
Method

This chapter describes the study approach, experimental plan, the test facilities, and the methods of sample collection and analyses.

3.1 Overall Study Approach

Full-scale codigestion demonstrations were conducted at the Silicon Valley Clean Water (SVCW) facility located in Redwood City, Calif. The digester named "Digester No. 2" at SVCW was used for all the tests in this study and is referred to as "test digester" in this chapter. The study approach involves the following tasks:

- Benchmarking of test digester operations at SVCW
- Tested under two sludge loading conditions
- Codigestion with addition of FOG to the digester
- Tested under three FOG/sludge loading conditions
- Novel FW preprocessing and codigestion demonstration
- Tested under two FW/sludge loading conditions

The benchmarking tests were carried out to determine the effect of only sludge digestion. The amount of VS added from FW and/or FOG was increased strategically with each test. This strategic approach has shown to optimize the process of codigestion by affecting digester chemistry, dewatering, and cake quality (odor control) in prior work by the project team. In addition, it has helped to mitigate issues such as volume expansion. This is demonstrated in this study through sequential addition of increasing amounts of FOG and FW to digester feed sludge. The following sections describe these tasks in detail.

3.2 Test and Evaluation Activities Description

During each full-scale test, the test digester was operated at the target loading condition and monitored for steady state by measuring gas production, volatile solids reduction (VSR), unit gas production, and digester effluent VS percentage. Once steady state was reached, samples were collected for either on-site analysis at the SVCW laboratory (Table 8), or sent for other analysis to Bucknell University`s Environmental Engineering and Science Laboratory in Pennsylvania and Atmospheric Analysis and Consulting (AAC) Laboratory in California.

Table 8: Sample Analyses Performed On Site at SVCW Laboratory

Parameter	Analytical Method	Samples	Frequency*
pH	SM 4500	Feed, digester sludge, FOG, FW	Once a week/Daily
Total Solids (TS) & Volatile Solids (VS)	SM 2540	Feed, digester sludge and FOG, FW	Once a week/Daily
Chemical Oxygen Demand (COD) (Total and soluble)**	Method 8000 (HACH COD Vials)	Feed, digester sludge and FOG, FW	Once a week/Daily
Total Phosphate**	Method 10209 (HACH P Vials)	Feed, digester sludge and FOG, FW	Once a week/Daily
Ammonia, mg/L NH_4-N	Ammonia electrode	Feed, digester sludge and FOG, FW	Once a week/Daily
Electrical Conductivity (EC)	Conductivity probe	Feed, digester sludge and FOG, FW	Once a week/Daily
Foam Potential	Aeration method	Feed, digester sludge and FOG, FW	As needed
Alkalinity	SM 2320B	Digester sludge	Once a week
Volatile Acids (VA)	SM 5560C	Digester sludge	Once a week

***Frequency of sampling varied from daily (during tests) to weekly (during steady state monitoring)**

**** Method uses testing vials manufactured by HACH company which manufactures analytical instruments and reagents widely used in standard analyses of water and wastewater.**

Source: Kennedy/Jenks Consultants

Table 9 lists the analyses performed by Bucknell University’s Environmental Engineering and Science Laboratory, headed by Dr. Matthew Higgins, which has world-renowned facilities for dewatering and other biosolids odor analyses. Such specialty analyses are not available elsewhere. AAC is a certified specialty air and gas analyses laboratory.

Table 9: Analyses Performed by External Laboratories

Parameter*	Samples	Analytical Method
Cations (mg/L)	Digester sludge	GC-MS
Dewatering and Polymer Demand	Digester sludge	% Cake Solids, capillary suction time (CST)
Cake Odor	Digester sludge	Headspace Method
Rapid Rise	Digester sludge	Volume Expansion Method
C-H-N -O Content	Digester sludge	CHN Analyzer
Gas Composition/mercaptans/H_2S**	Raw biogas	ASTM D-3588 Analyses (GC/SCD/FID/TCD)

***Analyses were performed once every test period. **Biogas analysis was performed at AAC labs in California. All other analyses were performed at Bucknell University in Pennsylvania.**

Abbreviations: GC = gas chromatograph; SCD = Sulfur Chemiluminescence Detector; FID = Flame ionization detector; TCD = Thermal conductivity detector

Source: Kennedy/Jenks Consultants

Digester influent and digested sludge were sampled daily and analyzed on site as described in Section 3.4. Concurrently, plant data was collected regularly from the supervisory control and data acquisition (SCADA) system, which recorded data continuously. A list of the on-line data collected during the study is provided in Table 10. Other data such as plant polymer feed and other operational notes were obtained from operations personnel.

Table 10: Plant Operations Data (SVCW)

Parameter	Frequency
Sludge Flow Data (PS, TWAS, Digested Sludge)	Continuous from SCADA data collection
FOG, Process Water, and FW Flow Data	Daily
Gas Flow (Digesters, Co-generation Feed, Flare)	Continuous from SCADA data collection

Source: Kennedy/Jenks Consultants

3.2.1 Benchmarking Tests

The test digester was operated at two different sludge loadings to benchmark the operations prior to addition of codigestion feed stock. No FOG or FW was added to the digester during the benchmarking tests. The two increasing levels of sludge VS loading would help establish gas production, dewatering, and cake odor characteristics of sludge digestion. The first loading test marks the typical operating condition of the digester. The next test represents what the combined loading would be when sludge and the organic waste are codigested in subsequent tests of the project. The digester was operated at the target loading rate and monitored for one to two months to ensure steady-state conditions had been achieved. After steady-state conditions had been confirmed, the digester operation was continued at the target loading conditions for approximately two weeks and samples were collected, analyzed on site, and sent to outside labs for analysis. The loadings are listed in Table 11.

Table 11: Benchmarking Test Loadings

Timeline	Target Loadings (lbs VS/cu.ft./day)
Benchmarking Test 1	0.07
Benchmarking Test 2	0.11

lbs VS/cu.ft./day = pounds VS/ cubic feet/day

Source: Kennedy/Jenks Consultants

3.2.2 FOG Codigestion

For the tests using FOG codigestion, the test digester was operated at three different sludge and FOG loading conditions as shown in Table 12.

Table 12: Full-Scale Codigestion Strategy Schedule

Timeline	Loadings (lbs VS/cu.ft./day)	FOG VS : Sludge VS (%)
FOG Test 1	0.09 (~0.08sludge + ~0.01 FOG VS)	12.5
FOG Test 2	0.1 (~0.08 sludge + ~0.02 FOG VS)	~26
FOG Test 3	0.1 (~0.07 sludge + ~0.03 FOG VS)	~48

Source: Kennedy/Jenks Consultants

For FOG Test 1, steady-state operating conditions were attained through acclimation at the target load over a period of approximately 5 weeks prior to sample collection and analysis. However, for FOG Tests 2 and 3, sustained supply of the targeted quantity of FOG were not received at the plant. Sample collection for these tests were to be scheduled based on the delivery of large (achieving target) quantity of FOG from local cafeterias of commercial institutions. Large FOG deliveries were typically received once every two to three months over a three- to four-day period. Between FOG deliveries, the digester was operated with targeted VS loading of sludge and available loading of FOG to have the microorganisms somewhat acclimated to the test conditions. Upon receiving the large FOG deliveries, acclimation ranged from two to five days after which samples were collected and sent for analysis.

3.2.3 Food Waste Preprocessing and Codigestion Demonstration

The digester was operated at two different FW loadings to determine the effect of preprocessed FW on digestion. FW was added to the digester to the extent that the sludge to co-waste ratios were similar to those of the FOG tests. Preprocessed FW (OREX extract) was obtained from the Recology facility in South San Francisco. It was polished on site at SVCW with the facilities described in Section 3.3.3. Prior to each test, the digester was operated at each loading condition and monitored for steady state by measuring gas production, VSR, unit gas production, and digester effluent VS percentage. The steady-state monitoring period for each FW test ranged from one to two weeks. Once steady state was reached, samples were collected and sent out for analysis. On-site analysis was conducted as described in Section 3.3. Table 13 lists the preprocessed FW codigestion loadings used in the study.

Table 13: Novel Food Waste Preprocessing and Codigestion Demonstration Schedule

Timeline	Loading (lbs VS/cu.ft./day)	Food VS: Sludge VS (%)
FW Test 1	0.05 (~0.047 sludge + <0.01 FW VS)	~12.5
FW Test 2	~0.055 (0.045 sludge + ~0.01 FW VS)	~25

Source: Kennedy/Jenks Consultants

3.2.4 Benefits Evaluation

An economic analysis was performed using the revenue and cost items summarized in Table 14. The change in costs of polymer addition and sludge hauling costs due to dewatering were taken into consideration. Non-economic benefit analysis was performed by estimating the GHG emissions that would be avoided by diverting FW from landfills to anaerobic digestion for biogas and energy production. The proprietary in-house Kennedy/Jenks Consultants waste to energy (WTE) model was used for evaluating the economic benefits. The EPA waste reduction model (WARM) was used for the GHG reduction estimation.

Table 14: Boundaries for Economic Analysis

Expenses	Revenues/Costs Avoided
FW preprocessing costs by OREX	Costs avoided for FW sorting and separation by OREX
Food waste receiving station construction cost	Energy produced from biogas
O&M costs of FW preprocessing and codigestion	FOG and FW tipping fees
Polymer addition	Avoided electricity cost
Solids dewatering	Avoided fuel cost (currently, SVCW uses natural gas to fulfill capacity of cogeneration system)

Abbreviations: O&M = Operations and maintenance

Source: Kennedy/Jenks Consultants

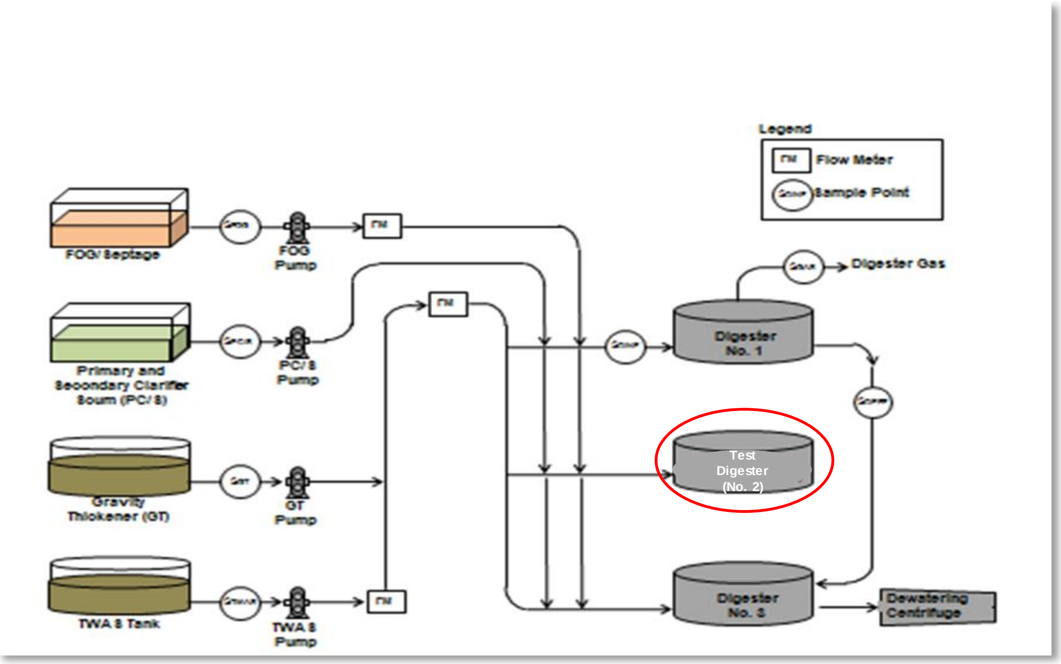
3.3 Test Facilities Description

Full-scale demonstrations were conducted at the SVCW wastewater facility located in Redwood City, California. The SVCW WWTP serves about 200,000 people and businesses in the mid-Peninsula area south of San Francisco. The wastewater treatment train consists of primary clarifiers, coupled fixed film-activated sludge biological treatment, secondary clarifiers, granular media filtration, and disinfection.

3.3.1 Solids Processing and Digesters

The solids processing train at SVCW has three 1.6 MG anaerobic digesters (Digesters No. 1, No. 2, and No. 3) to digest thickened sludge from primary and secondary clarifiers. Only Digester No. 2 was dedicated to this project. Any mention of "digester" in this report refers to the test Digester 2. A schematic of the solids handling process is presented in Figure 5.

Figure 5: Schematic of Solids Handling Process in SVCW



Source: Kennedy/Jenks Consultants

The facility has additional digestion capacity available, as only two of the three digesters are necessary to handle the plant's sludge flows. This excess digester capacity is one of the main drivers for adopting codigestion in the facility. Digester No. 2 received controlled loadings of the primary and secondary thickened sludge, and of FOG and FW (for the codigestion tests) during the test. Digester No. 3 received anaerobically digested sludge discharged from Digester No. 2. Some sludge, scum, and FOG were also fed to Digester No. 3 when the loading from these streams exceeded the loading setpoint for Digester No. 2. Digested sludge from Digester 3 was sent for dewatering using one of the two fan presses in the plant. Typical solids content of the dewatered cake is approximately 17 to 20 percent. Table 15 provides the digester details.

Table 15: Existing Digester Summary

Digester	Details
Number	3 (only 2 in service)
Inside Diameter (ft)	96
Side Water Depth, (ft)	31
Volume (gal, each)	1,700,000
Working Pressure (inches H_2O)	10
Mixing Design Turnover Rate (times/day)	8-10
Number of nozzles for mixing	2
Number of mixing Pumps/Digester	1
Pump type	Mixed Flow
Mixing nozzle size (in, suction/discharge)	18/18
Flow (gpm)	10,000

gpm: gallons per minute

Source: Kennedy/Jenks Consultants

3.3.2 FOG Receiving Station

FOG waste was brought into the FOG receiving station via local haulers from commercial generators such as restaurants, cafeterias, and grocery stores in SVCW's service area. The receiving station had a Beast unit (FLO-Beast by Enviro-care) that removed debris and cleaned the FOG. The Beast unit consisted of a short influent tank, a rotating drum screen, and an auger trough. The FOG Beast interface panel was used by the grease hauling operators to record the date and time, volume of FOG delivered, and the volume of heated process water used for each load. This triggered the Beast system to start the flow of the process water. The hauler was connected to the inlet of the Beast unit via a hose coupling connector. As the pumped flow entered the tank, it was discharged directly into the rotating screen. As the screen rotated, debris was captured, carried around the drum screen, and deposited into the auger trough. From the trough, the debris was washed, dewatered, and conveyed into the waste collection hopper. A measured flow of heated process water was used by the Beast unit to convey the flow of FOG. This helped dilute FOG and prevent it from sticking onto the Beast equipment. The pretreated FOG was then stored in two FOG holding pits and pumped into the digesters. The FOG pits had chopper pumps to keep the contents mixed. Flow meters were used to measure the quantity of FOG pumped into the pits by the haulers, the process water flow for the FOG, and the FOG fed to the digesters. Level sensors installed in the FOG holding pits provided operational control based on pit levels. Figure 6 shows the FOG receiving station.

Figure 6: FOG Receiving Station Showing the Beast

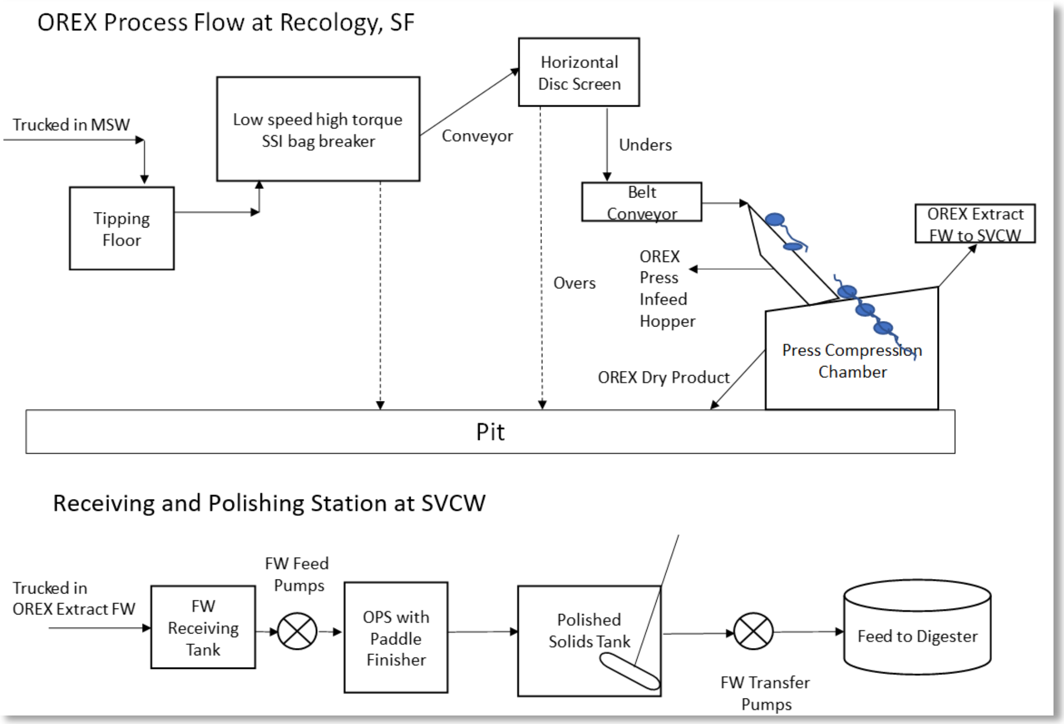
FOG Receiving Station On-site at SVCW

Source: Kennedy/Jenks Consultants

3.3.3 Food Waste Preprocessing and Polishing

After FW was separated from mixed solid waste using the OREX unit at the Recology facility, it was trucked to the demonstration site at SVCW. Further polishing of the extracted FW was achieved using an OPS unit. Here, finer inert materials were removed prior to the FW extract being fed to the test digester. A process flow diagram of the selected two-step FW preprocessing method implemented for this study is shown in Figure 7.

Figure 7: Process Flow for OREX (Top) and OPS (Bottom)



Source: Kennedy/Jenks Consultants

3.3.3.1 OREX Preprocessing

OREX was selected as the first step for separating FW from the large inorganic/non-digestible material in mixed solid waste (as discussed in Section 2.1.3.1). Figure 8 shows the OREX press installed at the Recology facility in San Francisco, where MSW was collected and processed prior to being hauled to the demonstration site at SVCW.

Figure 8: Organic Extrusion Press

Located in Recology, San Francisco; L: Side view of the OREX with the product conveyor; R: feed hopper into the OREX

Source: Kennedy/Jenks Consultants

3.3.3.2 Food Waste Receiving and Polishing Station

The purpose of the on-site FW polishing facility was to receive, polish, dilute, and transfer the FW to the digesters. The existing FOG receiving station at SVCW was modified and retrofitted to accommodate the FW polishing and receiving station. The major components of the FW preprocessing facility at SVCW included a receiving tank with a mixer, a submersible feed pump to convey the hauled FW to the paddle finisher, a 30-hp paddle finisher with two paddles and a helix screen (hole size of 0.25-inch diameter), a polished solids tank, and a transfer pump to feed the polished waste to the digester. The receiving tank contained about 20 spray water nozzles that provided process water for dilution of FW, two flowmeters to measure the amount of FW added to the digester and the amount of process water added to tank for dilution, level indicators in the tanks, and flow control valves. Figure 9 shows the FW receiving and polishing station at SVCW.

Figure 9: FW Receiving and Polishing Station

Located on-site at SVCW

Source: Kennedy/Jenks Consultants

3.4 Sampling and Analysis

Field and laboratory analyses were performed during the benchmarking, FOG codigestion, and FW demonstration phases of the project. Digester influent, digested sludge, and digester gas samples were collected for various analyses as described in the following sub-sections.

3.4.1 Sample Collection, Handling, and Shipping

An overview of the sample analysis plan is provided in Tables 8 and 9. Samples were analyzed on site in SVCW's laboratory, at Bucknell University (Lewisburg, Penn.), and at Atmospheric Analyses and Consulting, Inc. (AAC) laboratory (Ventura, Calif.). In addition, data from SVCW's compliance program were used, as appropriate, for this study. The following sections describe samples that were collected and sent to external labs for analysis.

3.4.1.1 Biogas Samples for AAC Laboratory

Raw biogas from the digester was collected in the canisters provided by the AAC labs and shipped back for analysis. A flow controller valve with a gauge was provided by the AAC. Prior to sampling, the canister was fitted with the flow controller valve and connected to the sampling line. The sampling was completed when the gauge read -5-inch Hg (inches of mercury, a unit of measurement for pressure).

3.4.1.2 Digester Samples for Bucknell University Laboratory

Samples analyzed at the Bucknell University were collected in the field and shipped overnight using appropriate containers, coolers, and preservation methods. Each sample was placed in an appropriate plastic container (Nalgene carboy bottle) labelled with the date and sample information. Each sample container was closed with an air- and liquid-tight cap. Duct tape was wrapped over the cap to prevent it from coming loose in transit. Soft packing materials were placed in the cooler to prevent movement of the containers while in transit. The cooler was also sealed tightly with duct tape and shipped overnight to the Bucknell University lab. Digester feed and effluent samples were prepared for shipping as described.

- Digester feed: A representative one-liter sample of thickened primary sludge and thickened waste activated sludge (TPS and TWAS) feed to the digester was collected for all the tests. The samples were cooled in a refrigerator at less than 4°C (39 °F) and placed in a cooler (separate from the digester effluent) with ice packs to help maintain a low temperature during shipping. In addition, for the codigestion tests, a representative 500-milliliter (mL) sample of FOG or FW was shipped on ice.
- Digester effluent: About 12 liters of digester effluent were collected from Digester No. 2 for all the tests (benchmarking, FOG codigestion, and FW codigestion). The samples were de-gassed for several hours by leaving the container cap open to atmosphere or by using a vacuum line to expedite the degassing. The sample container was periodically shaken to mix during the degassing. After the samples were degassed, the containers were tightly sealed and placed in a shipping box with no ice. After the samples arrived at the lab, they were stored in a refrigerator at less than 4°C until they were processed.

3.4.2 Analytical Methods

All digester feed and effluent testing was performed according to standard methods (American Public Health Association [APHA] 2012) or specific protocols developed for laboratory testing, which are described in the following sections.

3.4.2.1 Food Waste Respirometry

Prior to the full-scale codigestion with FW, respirometry tests were conducted to estimate gas production from FW material. Nine 500-mL Wheaton respirometer bottles were filled with 300 mL of digester sludge. Ten grams of FW extracted from the OREX press (from two separate testing days) were added into three of the sludge bottles. The bottles filled with only sludge were marked as control. The bottles were purged for one minute using 60 percent methane (CH_4)/40 percent CO_2, and then tightly closed with a lid containing a rubber septum. All the bottles were placed into a water bath maintained at a temperature of 37°C (98.6 °F). A 20-gauge needle with a gas line was inserted into the septum. This line was connected to the respirometer and laptop for data collection. The respirometer was used at the low anaerobic setting to record gas production. The experimental set-up is shown in Figure 10.

Figure 10: Respirometry Setup at Bucknell University

Source: Dr. Matthew Higgins, Bucknell University

3.4.2.2 Standard Wastewater Tests

The sample analyses conducted at the on-site laboratory at SVCW included standard wastewater tests for TS, VS, COD, pH, alkalinity, volatile acids, and nutrient content.

- TS, VS and COD: Tests for TS and VS were performed according to the APHA's Standard Methods (2012). COD was performed by the HACH Company COD vials (TNT (Test `N Tube™) 822/823)) after appropriate dilutions for each of the unfiltered samples. Samples filtered through a 0.45 micron (µm) filter were diluted and used for soluble COD. Occasionally, the thickened PS feed was too clumped and had to be blended in a lab blender. In some cases, the FOG also had to be blended to get a representative sample. All dilutions were made with ultrapure water.
- pH, EC, alkalinity and volatile acids: pH was measured using a pH probe meter (model: Thermo Orion Star A 221). Alkalinity was measured by the standard methods (SM) 2320 B. Volatile acids (VA) were measured by SM 5560 C. Individual VAs were further measured by Bucknell lab for some of the tests. EC was measured using a YSI 85 conductivity and salinity probe.
- Nutrients: Filtered and diluted samples were used for ammonia measurements by the Thermo Scientific Orion ISE ammonia/ammonium electrode (Thermo Fisher Scientific, Penn.). A three-point calibration curve pertinent to the ammonia concentration of the samples was made every time before starting the ammonia analysis using freshly prepared standards. The standards were made by diluting a 1000 parts per million (ppm) NH3 standard in volumetric flasks using ultrapure water. Prior to measuring the samples, a few drops of 10-N sodium hydroxide (NaOH) were added as an ionic strength adjuster (ISA). The samples were continuously stirred at a moderate speed using a magnetic stir bar and stir plate during ISA addition and analysis. The use of ISA

raised the solution pH to convert ammonium ion in the solution to ammonia gas, allowing it to be detected by the probe. Measurements were recorded once a stable reading was achieved.

- Samples for phosphorous were filtered, diluted appropriately, and measured using the HACH vials (TNT 844).
- For all analyses, if the samples were stored in the refrigerator, they were allowed to reach room temperature prior to analysis.

3.4.2.3 Rapid Volume Expansion Potential/Aeration Foaming Potential

Rapid volume expansion (RVE) potential tests were conducted to determine the effect of the codigestion on foaming. The method used was developed at Bucknell University in which samples of digester solids were placed in a special graduated cylinder. The top of the graduated cylinder was cut off to ensure a tight fit for the stopper. After the addition of digestate, the graduated cylinder was sealed with a stopper and the headspace was connected to a respirometer to attain gas production rates throughout the experiment. A stir bar was used for mixing. The system was fed with appropriate doses of feed, and the height of the solids was measured over time and the gas production data was collected via the use of a respirometer. The reactor was visually inspected to distinguish between foam expansion due to surface tension effects and solids expansion due to gas holdup. Eventually, the height measured was converted into a volumetric measurement and RVE was expressed as a percent of the original volume. The length of the tests was variable and depended upon when the digester solids reached their peak and began to collapse.

During the initial benchmarking tests, the digester was plagued by foaming episodes that were not related to the testing for this study. To understand and address the foaming episodes occurring the digester, the conventional aerated foaming potential test was conducted on site according to the method outlined in Pagilla and Subramanian (2014). The test consisted of diffusing air (1.5 L/min) at the bottom of a 2-liter graduated cylinder filled with 200 mL of digested sludge. Foam tends to build up in the cylinder as air bubbles are created, and the height of the foam layer provides an indication of the foaming potential of the sludge. This test was used to characterize two types of foam: unstable and stable foam. Unstable foam collapsed once the air supply was stopped, while stable foam persisted. The height measured was correlated to the mL markings on the graduated cylinder. Foaming potential was calculated in terms of an unstable foam and stable ratio, shown in equations 1 and 2 respectively (Pagilla and Subramanian 2014):

$$Unstable\ Foam\ Ratio = \frac{Maximum\ Foam\ Height\ (mL)}{Initial\ Height\ of\ Sludge\ (mL)} \qquad (1)$$

The working foaming potential (unstable foam ratio) thresholds used in this research were: non-foaming (0–1), mild foaming (1–2), average to severe foaming (greater than 2).

$$Stable\ Foam\ Ratio = \frac{Settles\ Foam\ Height\ (mL)}{Initial\ Height\ of\ Sludge\ (mL)} \qquad (2)$$

The foam stability (stable foam ratio) thresholds adopted during this research were as follows: non-foaming (0–0.2), mild foaming (0.2–0.5), average to severe foaming (greater than 0.5). It must be noted that such thresholds are plant specific and should be used with caution when comparing with other plants.

3.4.2.4 Viscosity

The rheological properties of sludge affect the mixing as well as the potential for RVE due to foaming and gas holdup. To evaluate the role of yield stress on the extent of RVE, viscosity of the feed and digester samples were analyzed using a Brookfield DVII Pro Viscometer. A sample of the digester solids was removed from the RVE test to measure various rheological properties. Shear rate–viscosity data was collected using a preprogrammed method by which the shear rate was slowly increased, and the shear stress and viscosity were measured at each shear rate.

3.4.2.5 Polymer Dose, Dewaterability, and Cake Odors

The dewaterability of the digester samples were analyzed using a laboratory protocol developed at Bucknell University (Higgins, Rajagopalan, et al., 016). A high-molecular-weight cation polymer (SNF INC FLOPAM FO 4650SH) was made to a 0.25 percent concentration on the day of the experiment. The optimum polymer dose was determined by establishing the polymer dose–response curve using capillary suction time (CST). A 500-mL sample of digestate was placed in a 2-L baffled, circular container. The polymer was added to the digester solids and mixed using a single paddle mixer rotating at 563 rpm (G ≈ 700/s; where G is the relative centrifugal force) for 30 seconds (s), followed by 54 rpm (G ≈ 50/s) for 90 s, after which the CST was measured. The dosage with the lowest CST was considered the optimum polymer dose and this sample was used in the dewatering tests.

Dewatering tests were performed by first gravity draining the solids on belt filter press fabric. After the solids were drained, they were placed in a specially designed belt filter press centrifuge cup. These cups comprised a piece of belt filter press fabric suspended approximately halfway up the height of the cup. The samples were then centrifuged at 2075 x g for 10 minutes, and the cake was scraped off the belt filter press fabric for TS and VS analyses. The cakes were also analyzed for their odorant production potential. Duplicate cake samples were generated and analyzed for each digestate sample.

The cake solids generated in the previous step were evaluated for the production of odor-causing sulfur compounds during cake storage. The volatile organic sulfur compounds (VOSCs) of interest were methyl mercaptan (MT), dimethyl sulfide (DMS), and dimethyl disulfide (DMDS), as they have been well correlated with cake odors (Higgins and Murthy 2006). VOSCs concentrations were analyzed using the headspace method developed by Virginia Tech and Bucknell University (Higgins et al. 2006). Ten grams of cake solids were placed in a 160-mL serum bottle that was sealed using a Teflon-coated butyl rubber septum. The serum bottles were stored at 25°C (77°F) in the dark. VOSCs and methane concentrations were measured in the headspace of the sample bottles on a regular basis during cake storage, typically every day, for two weeks or until the VOSCs had decreased below detection.

VOSCs were measured in the headspace using an HP 5890A Gas Chromatograph equipped with a flame ionization detector. A Restek Rt-Sulfur packed column measuring 2 meters long with an inside diameter of 32 mm was used. Both the injection port and detector temperatures were 200˚C (392 ˚F). The carrier gas was zero grade nitrogen at a flow-rate of 20 mL/min. Zero grade air and hydrogen were supplied to the flame ionization detector at flow rates of 450 mL/min and 20 mL/min, respectively. VOSCs were identified, calibrated and quantified by comparing the experimental chromatograms to those of pure standards.

3.4.2.6 Cation Concentration

Soluble cation concentrations, namely Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and NH^{4+} concentrations, were measured by ion chromatography on samples that were filtered through a 0.45 µm filter. Prior to filtering, the samples were centrifuged at 3000 x g for 15 minutes to separate the solids and improve filterability. Filtered samples were analyzed using a Dionex ion chromatography system (Thermo Scientific, Sunnyvale, California) with a CS12 column and conductivity detection, with self-generating suppression of the eluent (carrier solvent). This solvent was 20 mM methanesulfonic acid introduced at a flow rate of 1 mL/min.

3.4.2.7 Individual Volatile Fatty Acids (VFA)

The VFA concentrations were measured for C-2 (acetic) through the C-7 (heptanoic) compounds using an Agilent 5890 GC/FID (Agilent Technologies, Santa Clara, California) equipped with a 30 m x 0.53 mm x 1 µm film thickness Supelco Nukol Fused Silica capillary column (Catalog # 25357). Method has been previously detailed (Higgins and Rajagopalan 2017). Samples were first centrifuged at 3000 x g for 15 minutes, and the supernatant was filtered through a 0.45 µm filter; 0.5 mL of filtered sample was placed in a GC vial and diluted with 0.5 mL of deionized water. Fifty (50) µL of methanesulfonic acid was added to the vial and the vial was capped. Samples were auto injected into the GC at a volume of 1 L. The injector temperature was 238°C (460°F), and the oven was first held at 105°C (221°F) for 4 minutes, followed by a 5°C (41°F)/minute ramp to 145°C (293°F), followed by a 10°C (50°F)/minute ramp to 190°C (374°F) and a hold of 5.5 minutes. The detector temperature was 200°C (392°F).

3.5 Measurements and Validation for Energy Efficiency

Base Energy in San Francisco, California conducted a measurement and verification (M&V) demonstration for energy use and production. Data was gathered from SVCW for the various gas flow meters associated with each of the digesters and engines, for each test condition. This was used to estimate the power generated from the increased biogas production in the codigestion tests. SVCW also installed power loggers to isolate and estimate power consumption of the FOG station, FW preprocessing unit, and the dewatering units. This facilitated performing energy usage of all equipment dedicated for the codigestion study. Power loggers were also installed in the OREX unit to measure the power consumed for FW preprocessing.

Table 16 lists the energy consuming and producing components tracked for this study.

Table 16: Energy Use/Production (M&V by Base Energy)

Energy Consuming Components	Energy Production
Sludge transfer pumps	Biogas
FOG cleaning unit (Beast) and transfer pumps	Biogas
OREX Unit	Biogas
FW receiving and polishing Unit	Biogas
Dewatering fan presses at SVCW	Biogas

Frequency: Daily data from plant and periodic evaluation of OREX

Source: Kennedy/Jenks Consultants

CHAPTER 4
Results of Benchmarking Activities

This chapter describes the benchmarking tests used to establish the digester performance without the addition of organic wastes. SVCW Digester No. 2 was used for all the tests throughout this study and is referred to as "the digester" in this report. Any mention of "digester" in this chapter refers to the test Digester 2.

4.1 Testing Approach

The benchmarking activities consisted of the following:

- The test digester was operated without organic waste addition under two different sludge VS loading conditions:
  - Benchmarking Test 1: 0.07 lbs VS/ cu.ft. loading to represent typical digester loading conditions
  - Benchmarking Test 2: 0.11 lbs VS/ cu.ft. loading to represent increased loading conditions based on future codigestion loading
- Feed and digester sludge samples were analyzed to establish digester performance.
- Biogas and energy production were measured without organic waste addition.
- Dewatering characteristics, cake odor, and centrate quality were determined.

Typically, the digester was operated at each VS loading condition for at least one month to allow for steady state conditions to be reached. Table 17 shows the tests as well as typical sludge flow rate and sludge VS loading conditions for the two benchmarking tests. During Benchmarking Test 2, the digester experienced periodic foaming episodes. Some changes were made to the digester mixing pattern during this test to mitigate foaming. The mixing pattern was switched from top to bottom. It is important to note that such changes to the mixing regimen may impact digester gas production as well as sludge properties. These changes will be further discussed in the results.

Table 17: Timeline of Various Phases of the Benchmarking Study

Timeline	Average Vol of Sludge (GPD)	Average Loading (lb VS/ cu.ft./day)	Operation Variations
Benchmarking Test 1	~40,400	0.07	Digester No. 2 mixed 24/7.
Benchmarking Test 2	~70,000	0.11	Frequent rapid rise foam episodes in Digester No. 2 impacted gas production and gas measurement Digester mixing pattern was changed. Potential decreased Ferric chloride dose in digester

Source: Kennedy/Jenks Consultants

4.2 Benchmarking Tests – Results and Discussion

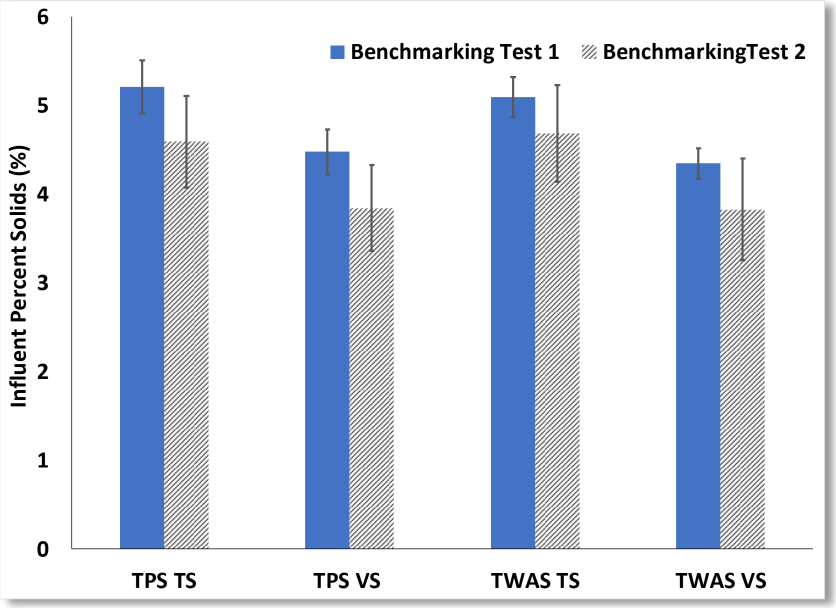
The digester benchmarking test results are presented in this section. The results shown in each graph are the average values, with the error bars depicting one standard deviation.

4.2.1 Influent Sludge Solids Content

The influent sludge characteristics varied during the project period due to differences in incoming sludge quality over time. The average TS and VS values of the thickened primary sludge (TPS) or thickened waste-activated sludge (TWAS) were measured during the two benchmarking tests. These results are shown in Figure 11.

Figure 11 shows the percent TS for the digester feed samples (TPS and TWAS) were approximately 5.2 percent during Test 1, and 4.5 percent during Test 2. The percent VS of the digester feed samples showed a similar trend, at 4.5 percent during Test 1 and 3.8 percent during Test 2. The percent solids were lower in the digester feed samples during Test 2, but consistent between the TPS and TWAS streams during the two tests. The variation observed between different samples (standard deviation) was typical of the day-to-day changes in influent wastewater characteristics. The percent solids in the TPS feed could also vary depending on the operation of the gravity thickener.

Figure 11: Average Daily Influent TS and VS for Each Test



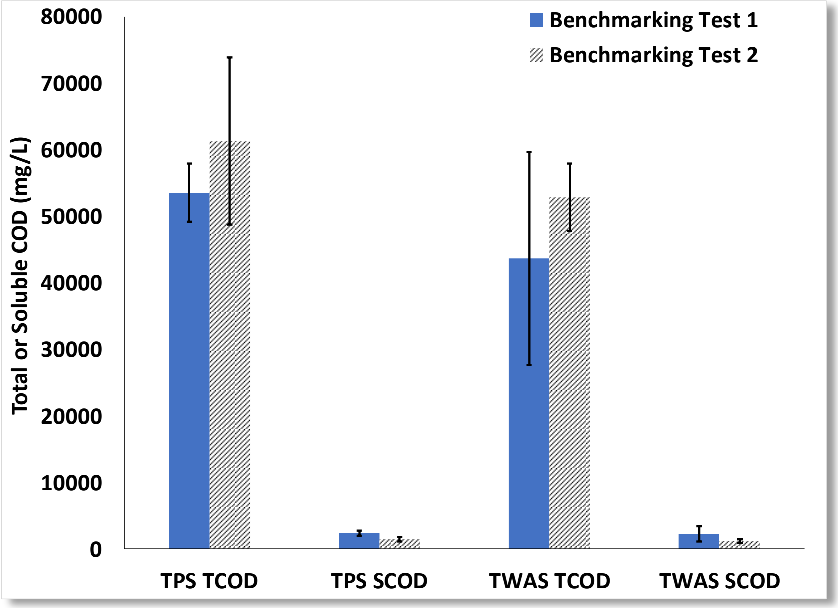
Note: Error bars represent standard deviation.

Source: Kennedy/Jenks Consultants

4.2.2 Influent Sludge Solids COD

The total and soluble COD of the influent TPS and TWAS was measured for Benchmarking Test 1 and Test 2. The results from the COD analyses are shown in Figure 12.

Figure 12: Average Daily Influent Total and Soluble COD



Note: Error bars represent one standard deviation.

Source: Kennedy/Jenks Consultants

The TPS influent total COD varied from approximately 53,000 mg/L to 62,000 mg/L and soluble COD of the TPS influent varied from 44,000 mg/L to 53,000 mg/L during the two benchmarking tests. The influent COD variation is largely due to the changes in feed characteristics coming in to the WWTP.

Typical trends for the carbon, hydrogen, and nitrogen (CHN) content, pH, electrical conductivity (EC), and ammonia concentration in the feed sludge (TPS and TWAS) during the benchmarking tests at SVCW are summarized in Table 18.

Table 18: Other Representative Characteristics of Feed Sludge

Parameter	TPS	TWAS
CHN*	41.7%: 6.8 %:2.8%	40.5%:6.5%:7.7%
pH**	6.2 ± 0.5	7.3 ± 0.2
Electrical Conductivity (mS/cm)**	2.6 ± 0.4	2.3 ± 0.5
NH_4-N (mg/L)**	125 ± 48.6	211 ± 100

mS/cm: millisiemens per centimeter

***Values from Benchmarking Test 1.**

****Average of the two benchmarking tests.**

Source: Kennedy/Jenks Consultants

The CHN content was found to be within typical values for wastewater sludge as reported in literature (Higgins and Rajagopalan 2017). Sludge pH was within the acceptable operating range and high enough to prevent acidic conditions to occur in the digester.

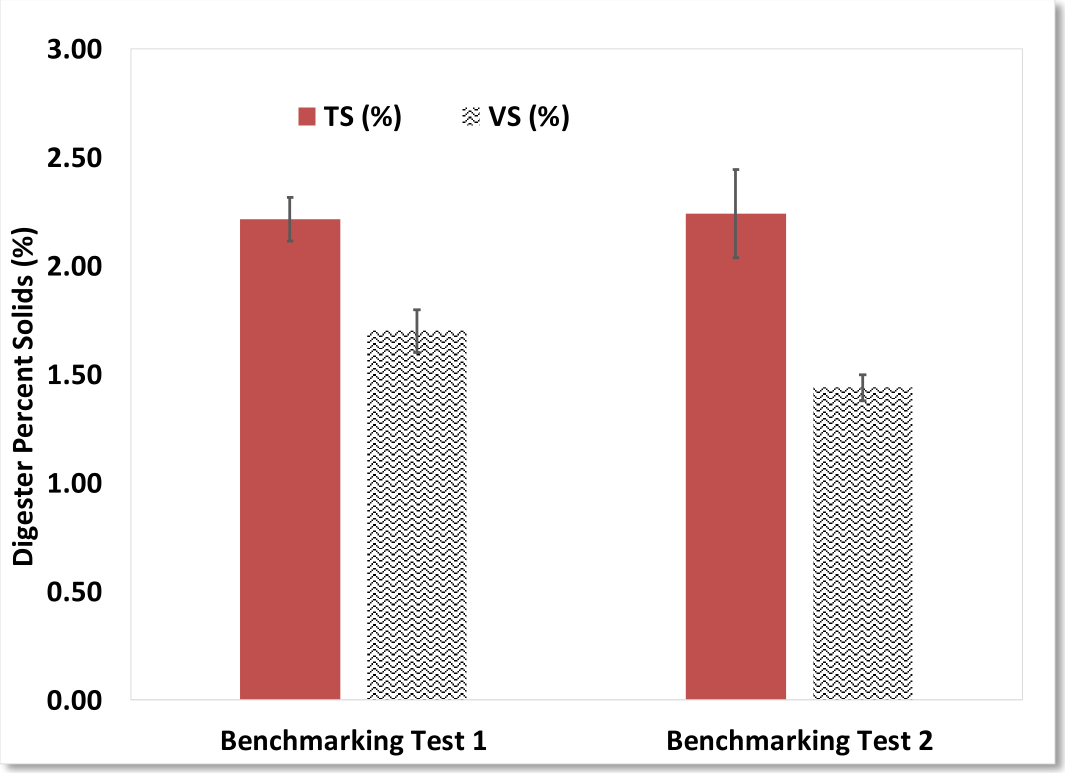
EC is widely used to estimate the total ionized constituents in water. Over the two benchmarking tests, EC did not vary significantly. However, ammonia in the feed sludge varied considerably over the testing period. Such swings in ammonia concentration coming into the plant vary with incoming flows to the plant.

4.2.3 Digester Performance – Solids, Gas Production, VSR, and Unit Gas Production

4.2.3.1 Digester Solids

The digester effluent TS and VS concentrations were measured during each benchmarking test. The results from these analyses are shown in Figure 13.

Figure 13: Average TS and VS in the Digester



Source: Kennedy/Jenks Consultants

Table 19 summarizes what TS and VS loading was applied in the sludge feed during each test, and what the resulting VS reduction (VSR) was calculated to be, based on the digester performance.

Table 19: Summary of Feed Sludge, Digester Solids, and Calculated VSR during Benchmark Testing

Test	Influent Sludge TS (lb/d)	Influent Sludge VS (lb/d)	Feed Sludge VS/TS Ratio	Dig Overall VS/TS Effluent Ratio
Benchmarking Test 1	17,333	14,839	0.86	0.77
Benchmarking Test 2	26,963	22,535	0.82	0.65

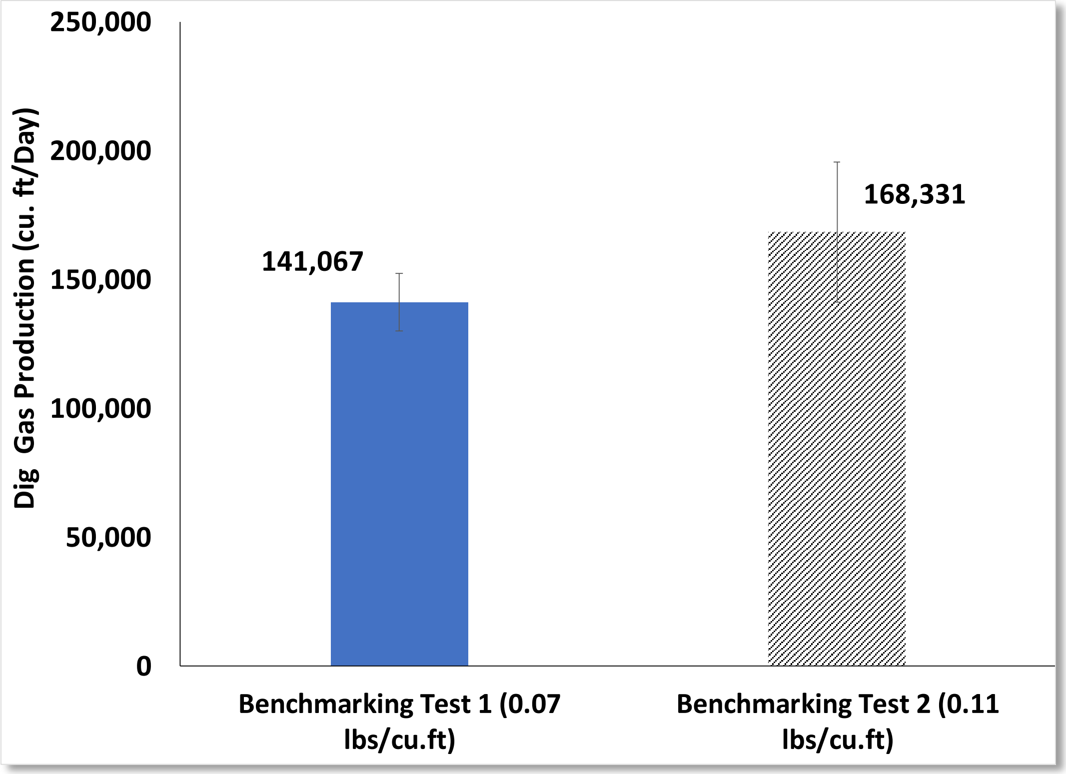
Source: Kennedy/Jenks Consultants

The digested sludge VS reached 1.75 percent during Benchmarking Test 1, and 1.5 percent during Test 2 (Figure 13). This was a 14 percent reduction from Test 1, despite the higher VS loading in Test 2 (Table 19). TS loading during Benchmarking Test 2 was increased by 55 percent compared to Benchmarking Test 1 and digester VS loading was increased by 52 percent for Test 2. However, the average VS/TS ratio for the digester feed sludge was maintained at approximately 0.84 for both tests. The digester effluent VS/TS was 0.77 for Benchmark Test 1, and 0.65 for Test 2. The digested VS results indicated that the percent VSR and gas production were higher during Test 2. These results are further discussed below.

4.2.3.2 Total Gas Production, VSR, and Unit Gas Production

The total gas production during each test was measured and is shown in Figure 14.

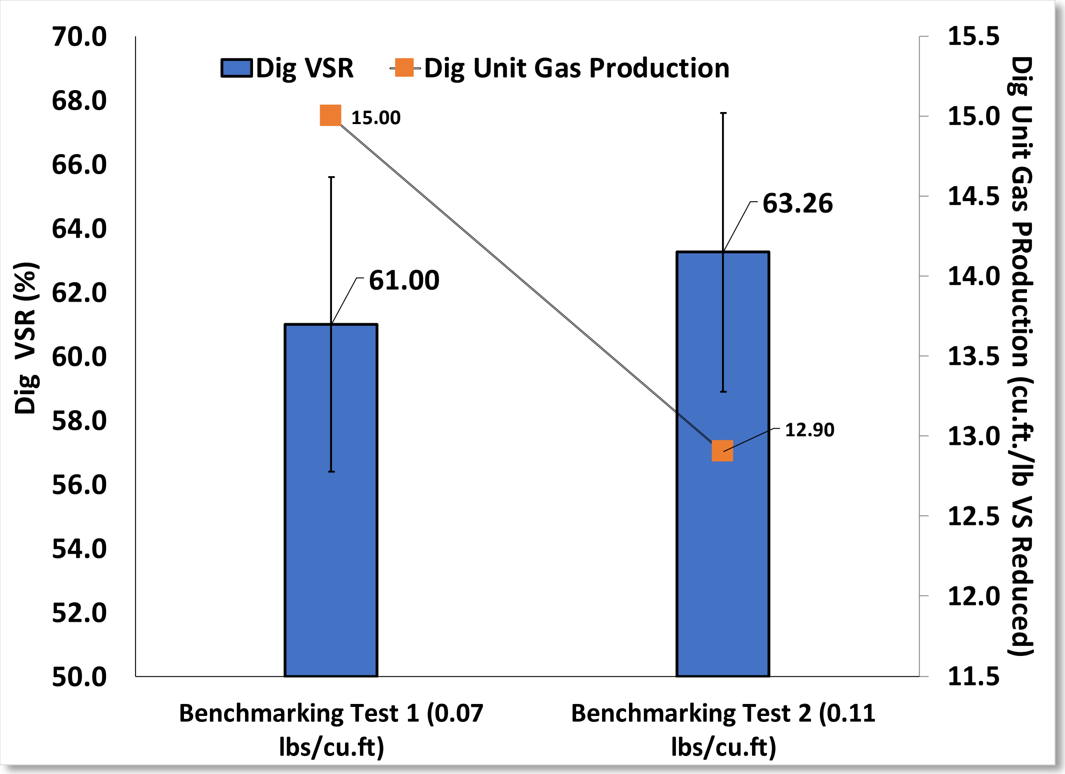
Figure 14: Comparison of Total Gas Production



Source: Kennedy/Jenks Consultants

In general, the results showed that increase in digester VS loading resulted in higher (19.3 percent) total gas production in Benchmarking Test 2. However, this increase in gas production was normalized based on the VSR taking place and is summarized in Figure 15.

Figure 15: Comparison of VSR and Unit Gas Production



Source: Kennedy/Jenks Consultants

The average VSR during Benchmarking Test 1 and 2 was 61 percent and 63 percent, respectively. The reasons for the higher VSR during Test 2 was not clear, as the test digester was considered to have reached steady state in both tests. The higher VSR for Test 2 may be attributed to non-representative sampling or non-homogenous conditions in the digester due to the foaming and subsequent mixing changes. When gas production was normalized based on the VSR for each test, results indicated that gas production during Test 2 was lower per unit of VS reduced compared to Test 1. The unit gas production dropped from 15 cu.ft. of gas produced/lb VSR in Test 1, to 12.9 cu.ft. of gas produced/lb VSR in Test 2. The lower unit gas production in Test 2 could be attributed to several factors. First, Test 2 has a higher VS loading along with a change in digester mixing pattern. The digester also experienced frequent rapid rise foam episodes during Test 2, which led to loss of seal events in the digester. This issue was unrelated to the testing in this project but resulted in gas production and gas metering losses, which potentially affected the results.

4.2.4 Gas Quality

4.2.4.1 Methane and CO_2 Content

The biogas produced during Test 1 and Test 2 was analyzed for its composition and quality. Table 20 shows the methane content and methane gas production along with CO_2 content.

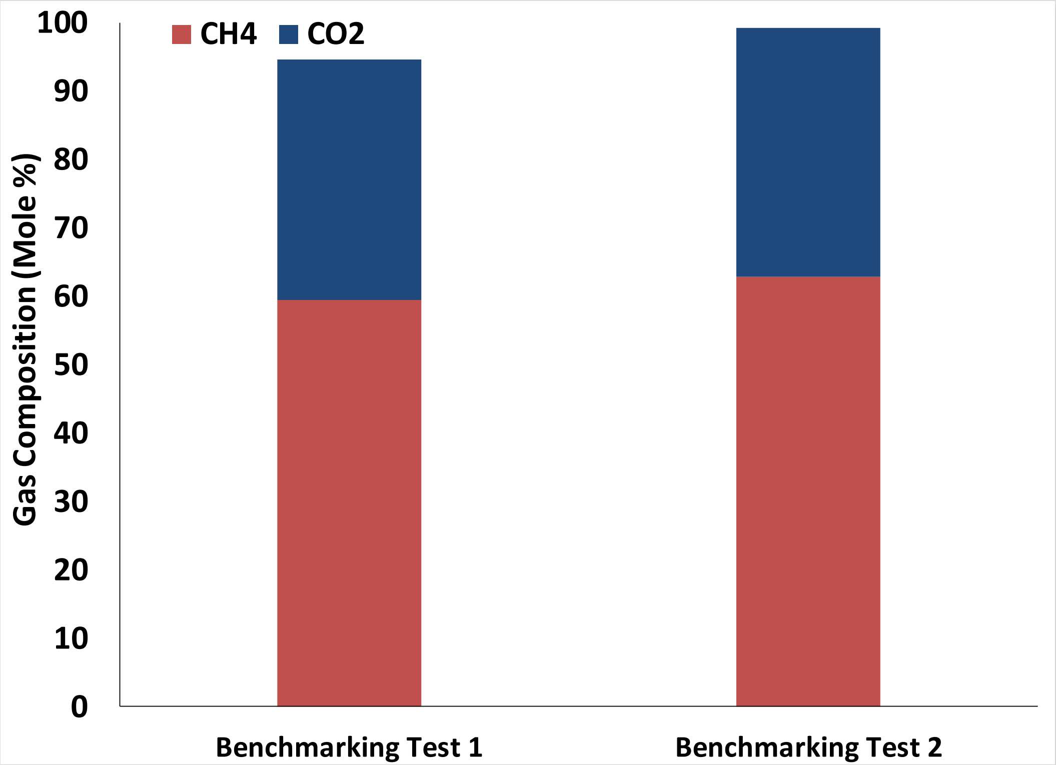
Table 20: Methane Content and Methane Production During Benchmarking Tests

Test	Biogas Production (cu.ft./day)	Average Methane Production (cu.ft./day)	Methane Content (%)	CO_2 Content (%)
Benchmarking Test 1	141,067	83,934	59.5	35.2
Benchmarking Test 2	168,331	105,712	62.8	36.5

Source: Kennedy/Jenks Consultants

Figure 16 shows the methane and CO_2 produced during the benchmarking tests.

Figure 16: Comparison of Gas Quality



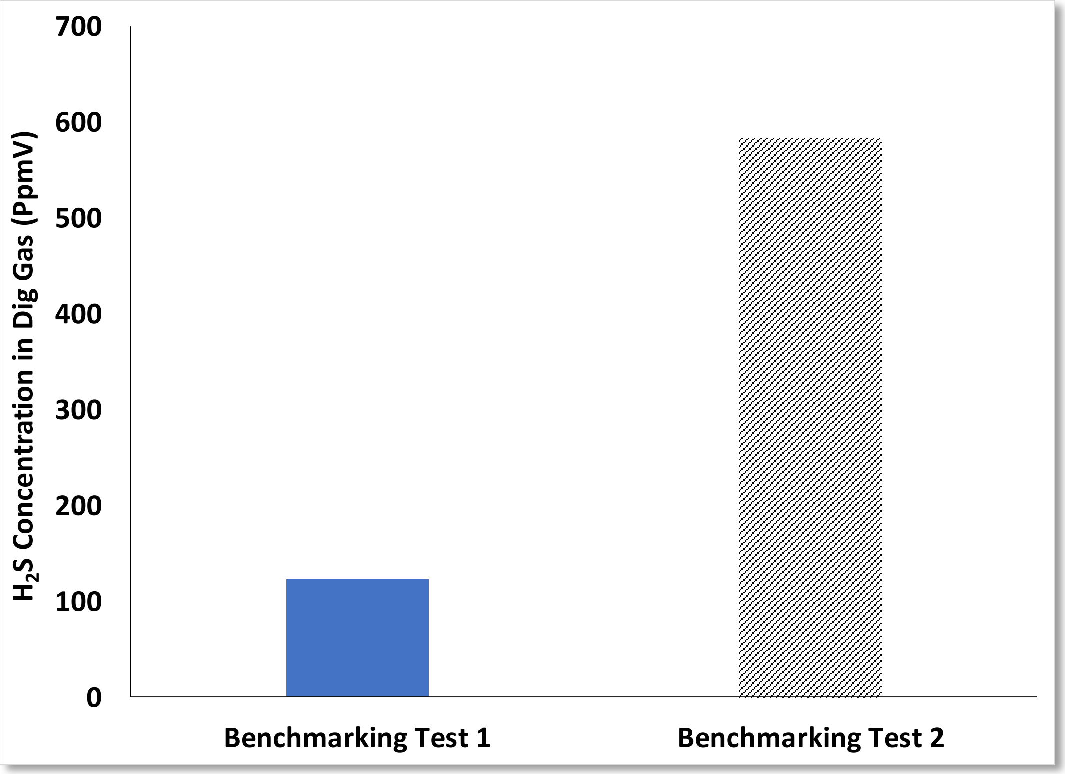
Source: Kennedy/Jenks Consultants

Biogas production was increased from 141,000 cu.ft./day during Test 1 to 168,000 cu.ft./day with higher VS loading during Test 2. The methane content of this biogas showed that Test 1 produced 83,900 cu.ft./day of methane (59.5 percent) while Test 2 produced 105,700 cu.ft./day of methane (62.8 percent). The CO_2 composition of the biogas remained unchanged during the two tests. The produced biogas had more methane content during Test 2.

4.2.4.2 Hydrogen Sulfide Production in the Digester

Hydrogen sulfide (H_2S) in biogas can be corrosive to downstream equipment, as well as toxic and odor-causing. Digester biogas requires that trace amounts of H_2S be removed prior to further use. Digester gas samples were analyzed for trace amounts of H_2S (Figure 17).

Figure 17: H_2S Production in Digester



Source: Kennedy/Jenks Consultants

The digester had an H_2S level of 120 ppmV (part per million by volume) in Test 1. The H_2S concentration increased almost five times in the second test. Typically, the plant adds ferric chloride ($FeCl_3$) to control H_2S but the plant staff faced dosing issues during Test 2. This may have spiked the H_2S levels, although the increased loading rate combined with the change in mixing conditions may also have affected the H_2S content in Test 2.

4.2.5 pH, Alkalinity, and Volatile Acids/Alkalinity in Digester

An imbalance between the acids produced during the various digestion steps and its consumption by the methanogens can lead to a pH decrease and subsequent digester failure. Sufficient alkalinity helps maintain pH and provide some buffering against this phenomenon. To evaluate if there was imbalance in the digester acid production, the digester pH, alkalinity, and volatile acids/alkalinity (VA/A) ratios were measured during the two benchmarking tests. The results from these tests are provided in Table 21.

Table 21: Digester pH, Alkalinity and VA/A Ratio

Test	Dig 2 pH	Dig. 2 Alkalinity (mg/L)	VA/A Ratio
Test 1	7.5 ± 0.02	4600	0.07
Test 2	7.7 ± 0.1	4575	0.06

Source: Kennedy/Jenks Consultants

The digester pH during the two benchmarking tests were 7.5 and 7.7, respectively. These levels are similar to the generally accepted values in the neutral range between 6.5 and 7.6 (Higgins, Rajagopalan, et al. 2016). A higher VS load during the Benchmarking Test 2 did not adversely affect the operating pH. The alkalinity during the two tests were not significantly different. The VA/A ratios were all below 0.10, which is considered a threshold level for stable operation (Wan et al. 2011).

4.2.6 Dewatering and Cake Odor Tests

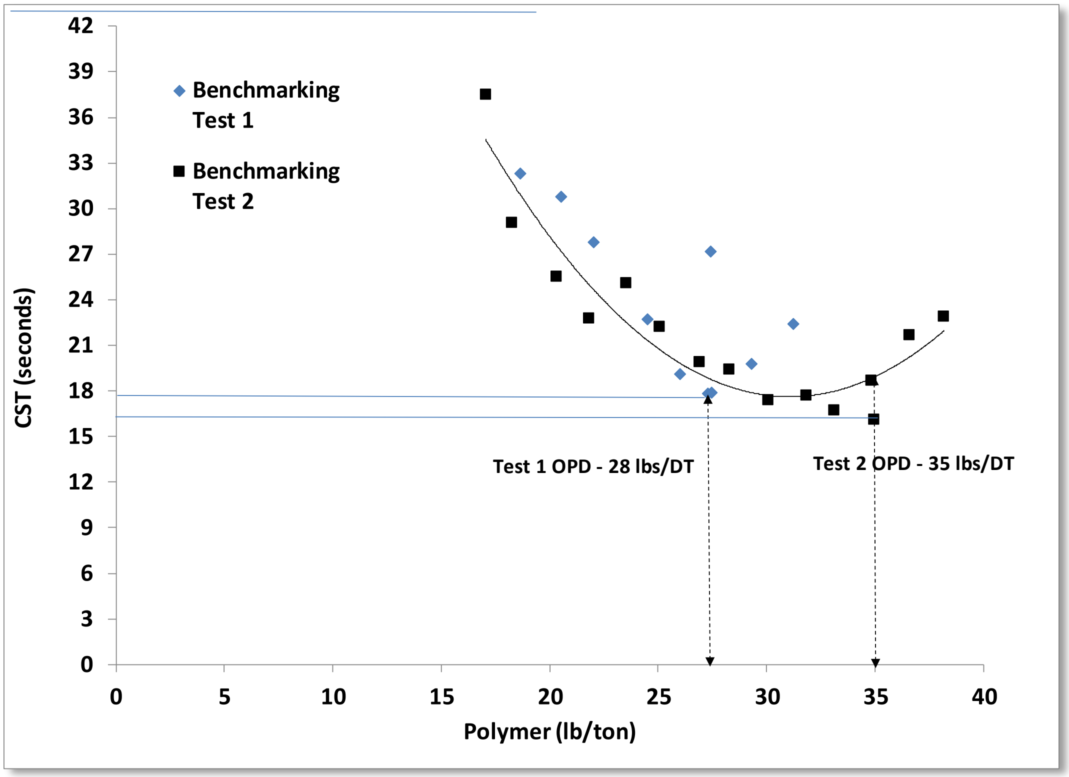
The results from digested sludge dewatering and odor tests are provided in this section. Dewatering characteristics of the digested sludge were evaluated using a high molecular weight cationic polymer (SNF FLOPAM 4650) that is commonly used for conditioning of digested solids. The following were determined during the dewatering and odor experiments:

- Optimum polymer dose (OPD)
- Percent solids in the dewatered cake
- Odor production from dewatered cake: TVOSC (total volatile organic sulfur compounds) such as methyl mercaptan (MT) and dimethyl sulfide (DMS)

4.2.6.1 Optimum Polymer Dose

The OPD for dewatering was determined by developing a curve based on the capillary suction time (CST) at a given polymer dose. CST is the time required for a certain volume of filtrate taken out of the sludge and sucked into a cloth or paper filter by capillary force. Briefly, CST is the time taken to dewater and is typically measured in seconds (Novak 2006). The main uses of CST include assessing the effects of conditioning on sludge filterability as well as determining the optimum dose of polymers for dewatering processes (Novak 2006). The dose producing the sample with the lowest CST is typically considered as the optimum polymer dose. A short CST, which is less than 20s, is indicative of a readily dewaterable sludge, while a long CST is representative of a poorly dewatering sludge. The CST curves for Benchmarking Test 1 and Test 2 are shown in Figure 18.

Figure 18: CST Curves for the Benchmarking Tests



Source: Kennedy/Jenks Consultants

Table 22 summarizes the OPD and the conditions for each test.

Table 22: Comparison of the OPD for Each Test with Operational Considerations

Test	Polymer Dose (lb/DT)	Comment
Benchmarking Test 1	28	Digester mixed 24x7
Benchmarking Test 2	35	Mixing pattern change/ Ferric chloride dosing issues

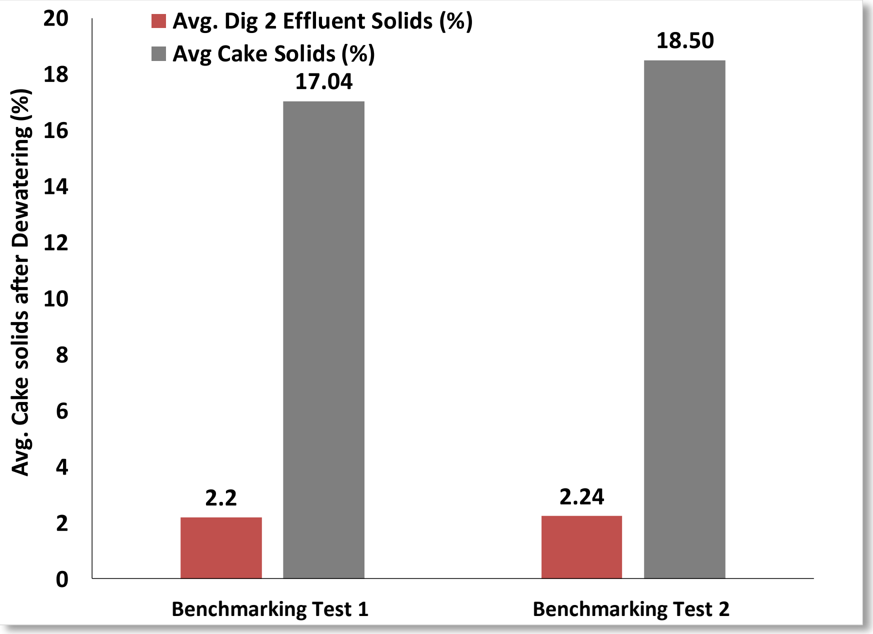
Source: Kennedy/Jenks Consultants

The OPD required for dewatering the digested sludge from Test 1 was approximately 28 lb/DT (dry ton) of polymer. The OPD for the Test 2 was 35 lb/DT. Polymer dose in Test 2 was potentially affected by both the mixing change and the reduced ferric chloride dosing, which may affect sludge properties and dewatering characteristics respectively.

4.2.6.2 Solids Dewatering

The dewatered TS content of the digesters is an indicator of the mass of sludge generated for hauling from the plant. If the dewatered cake solids (that is, percent TS in cake) is higher, the mass of sludge to be hauled will be lower. Using a bench scale dewatering unit at Bucknell University, the dewatered cake was measured for solids content (Figure 19).

Figure 19: Average Cake Solids after Dewatering



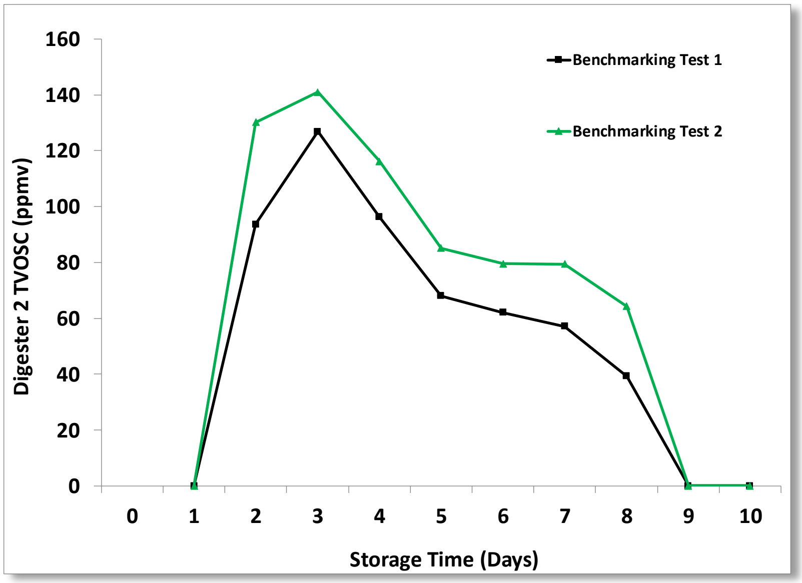
Source: Kennedy/Jenks Consultants

The digester sludge TS for the two tests were both approximately 2.2 percent. However, the percent TS in the dewatered cake from the two studies was 17 and 18.5, respectively. The higher percent TS of the dewatered cake in the Benchmarking Test 2 indicated that dewatering of the Test 2 digester sludge was more efficient. The mass of cake from Test 2 that needs to be hauled away could also be lower than that for Test 1, despite receiving a higher VS loading.

4.2.6.3 Cake Odor Production

Odor-causing TVOSCs were measured to track odor levels of the dewatered cake (Figure 20).

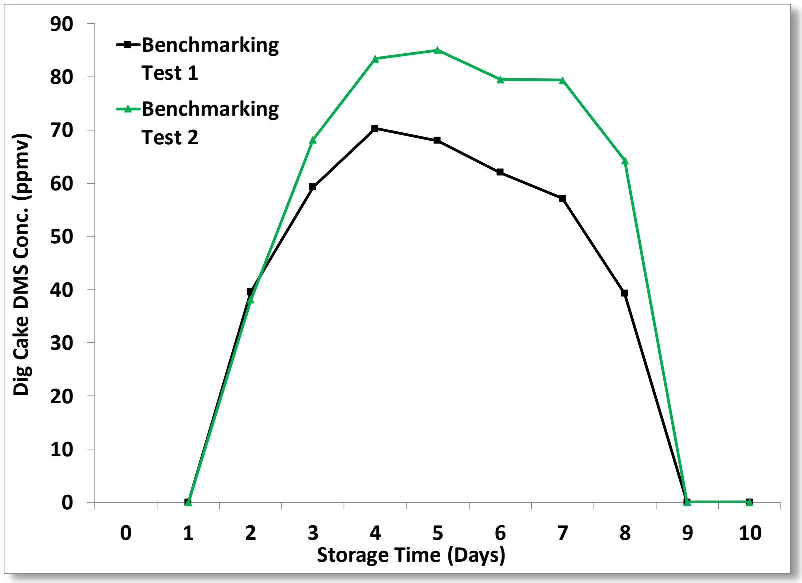
Figure 20: Peak Odor-Causing TVOSCs During Dewatered Cake Storage



Source: Kennedy/Jenks Consultants

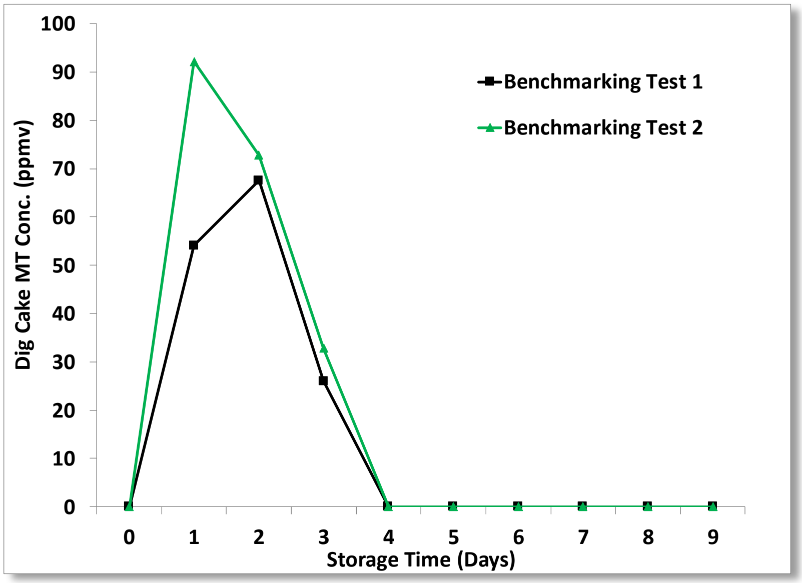
Individual compounds such as DMS and MT concentrations, which constitute the TVOSCs and are associated with cake odor, were measured (Figure 21 and Figure 22).

Figure 21: Peak Odor-Causing Compounds During Dewatered Cake Storage (DMS)



Source: Kennedy/Jenks Consultants

Figure 22: Peak Odor-Causing Compounds During Dewatered Cake (MT)



Source: Kennedy/Jenks Consultants

Peak levels of TVOSC (127 and 141ppmV) occurred after three days of dewatered cake storage for the Tests 1 and Test 2, respectively (Figure 20). The overall odor production gradually decreased and dropped to below detection levels by day nine for both tests. Peak concentrations of DMS (a constituent of TVOSC) in Test 2 was higher by approximately 21 percent over Test 1 (Figure 21) while MT (another constituent of TVOSC) level was 36.5 percent higher in Test 2 compared to Test 1 (Figure 22). MT concentrations dropped more quickly to below-detection limits, after only four days. The higher odor content in Benchmarking Test 2 may again be due to issues with ferric chloride dosing during the test.

4.2.6.4 Cations Concentrations and Monovalent/Divalent Ratio

Divalent cations such as Ca^{2+} and Mg^{2+} help stabilize the biofloc matrix by bridging the negatively charged groups, leading to good dewatering characteristics. Monovalent cations such as sodium ($Na+$), potassium ($K+$), and NH_4+ tend to destabilize the floc and worsen dewatering properties. Samples from each benchmarking test digester were analyzed to study the effect of monovalent/divalent (M/D) cation ratio on dewatering. Results are summarized in Table 23.

Table 23: Cation Concentrations in Digester

Species	Benchmarking Test 1	Benchmarking Test 2
Calcium (mg/L)	**351**	**274**
Magnesium (mg/L)	**56**	**15**
Sodium (mg/L)	**186**	**214**
Potassium (mg/L)	**107**	**203**
Ammonium (mg/L)	**1142**	**2023**
Free Ammonia (mg/L)	**40**	**71**
M/D Ratio	**3.5**	**8.4**

Note: Estimation based on Dig 2 pH in each corresponding test and temp of 35° C (95 °F).

Source: Kennedy/Jenks Consultants

Results from these tests showed that increased loading in the Benchmarking Test 2 increased the concentration of most cations in the digesters, except calcium and magnesium.

Prior to digestion, ammonium levels in the feed sludge during the Benchmarking Test 2 were 160/281 mg/L (TPS/TWAS). During Test 1, digester feed sludge ammonium concentrations were 91/140 mg/L (TPS/TWAS). The ammonium concentration in the digested sludge (Table 23) later rose to 1142 mg/L for Test 1 and 2023 mg/L for Test 2, due to the additional ammonia being released from solids during digestion. The elevated levels of ammonium in digester sludge during Test 2 compared to Test 1 can be partly attributed to the difference observed in the feed sludge. The alkalinity during the two tests was not significantly different (as discussed in Section 4.2.5) despite ammonia being a contributing factor to the alkalinity in the digesters.

The free ammonia levels in the two tests were calculated based on the ammonium concentration, pH, and temperature (Higgins and Rajagopalan 2017). Data from several reports indicate that free ammonia in the range of 80 to 150 mg N/L can inhibit digestion (Garcia and Angenent 2009; Yenigün and Demirel 2013). The calculated free ammonia concentrations in the two tests were 40 and 71 mg N/L, respectively, suggesting the free ammonia levels under these two loading conditions were not inhibitory.

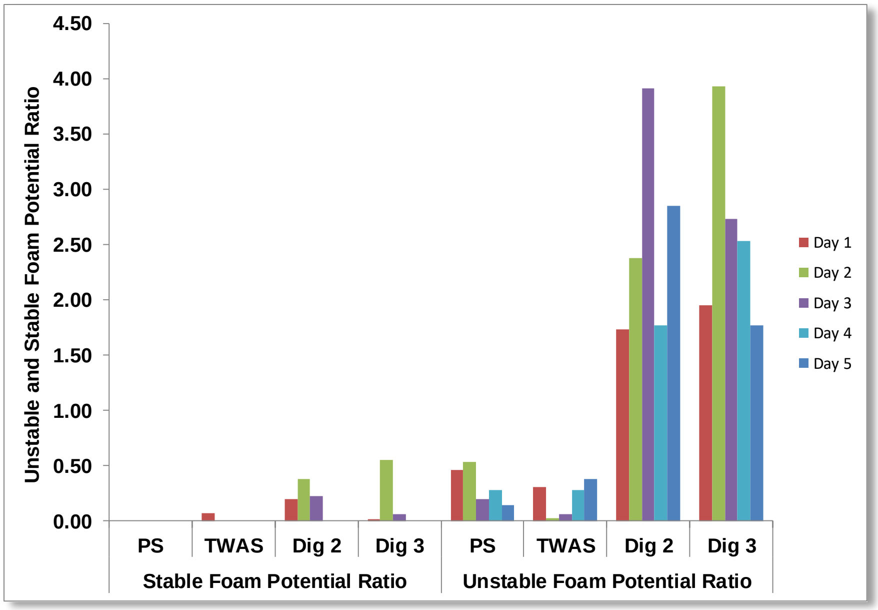
The monovalent/divalent cation ratio (M/D) in sludge samples are reported to affect OPD and percent cake solids during sludge dewatering. In general, the presence of divalent ions helps with bridging sludge solids and better dewatering. Monovalent cations bind to negatively charged sludge solids, and hinder polymer bridging and dewatering. An M/D ratio of less than 10 is considered favorable for dewatering (Higgins and Rajagopalan 2017).

The M/D ratios increased with increasing VS content in the two tests and are generally in the favorable range for dewatering. Though the M/D ratio is higher in Test 2, the dewatering is better than the Test 1, indicating that factors other than M/D potentially contributed to sludge dewatering behavior.

4.2.7 Digester Foaming Potential

Foam potential was not measured for Benchmarking Test 1 because no foaming occurred during the test period. Figure 23 shows the daily unstable and stable foam potential ratios for the feed and digester samples from Benchmarking Test 2.

Figure 23: Unstable and Stable Foam Potential Ratios Measured During Benchmark Test 2



Source: Kennedy/Jenks Consultants

The foam rating for different levels of foaming (mild, medium, and high) was provided in Section 3.4.2.3. Based on these levels, the working foaming potential (unstable foam ratio) thresholds used in this study were: non-foaming (0–1), mild foaming (1–2), and average to severe foaming (greater than 2). Based on these rating thresholds, the unstable foam potential of the feed sludge (PS or TWAS) indicated non-foaming values. The unstable foam potential of the digesters (Dig 2 and Dig 3), however, had higher values that ranged over the severe foaming threshold.

The foam stability (stable foam ratio) thresholds adopted during this research were as follows: non-foaming (0–0.2), mild foaming (0.2–0.5), average to severe foaming (greater than 0.5). The data for Benchmarking Test 2 showed that stable foam potential of the feed (PS or TWAS) was negligible. The stable foam potential of the digester sludge was in "mild" foam threshold range.

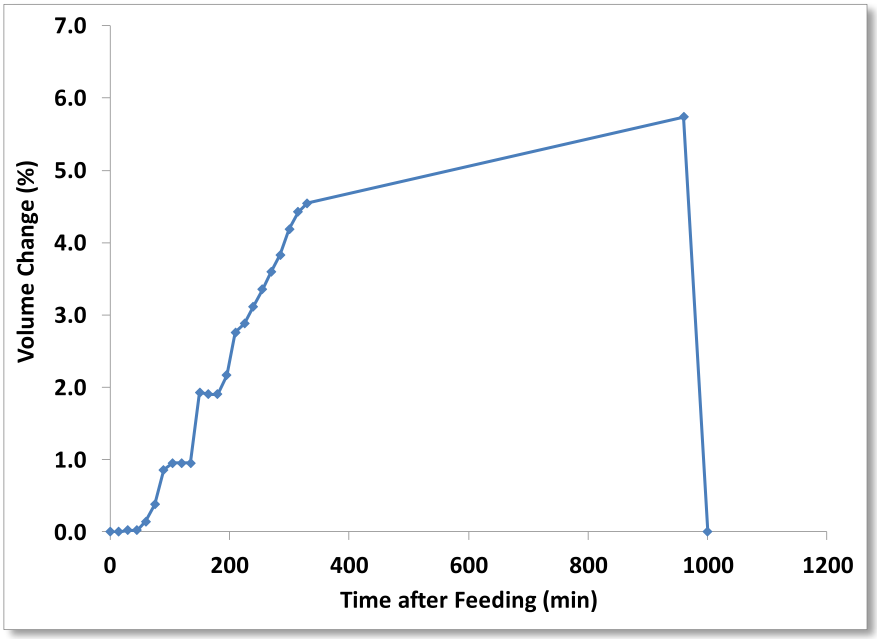
The higher values of the digester unstable foam potential when compared to the stable foam potential indicated that any foam formed is short lived. Negligible values of feed stable foam potential indicated that the foam created in the test digester during Test 2 was not due to feed characteristics. Unstable foam could be due to other physical phenomena such as gas entrapment and sudden release in sludge due to inefficient mixing occurring in the digester (Subramanian and Pagilla 2015). This was in accordance with the rapid volume expansion episodes observed in the digester as discussed in Section 4.2.8.

4.2.8 Rheology and Rapid Volume Expansion Potential

Viscosity and yield stress are important rheological parameters as they affect digester operations such as mixing, pumping, dewatering, and rapid volume expansion (RVE, also called rapid rise) due to gas holdup. The shear force exerted on sludge during mixing lowers the viscosity of sludge. When mixing is stopped, the viscosity of the sludge increases, which in turn facilitates gas hold up and eventual RVE.

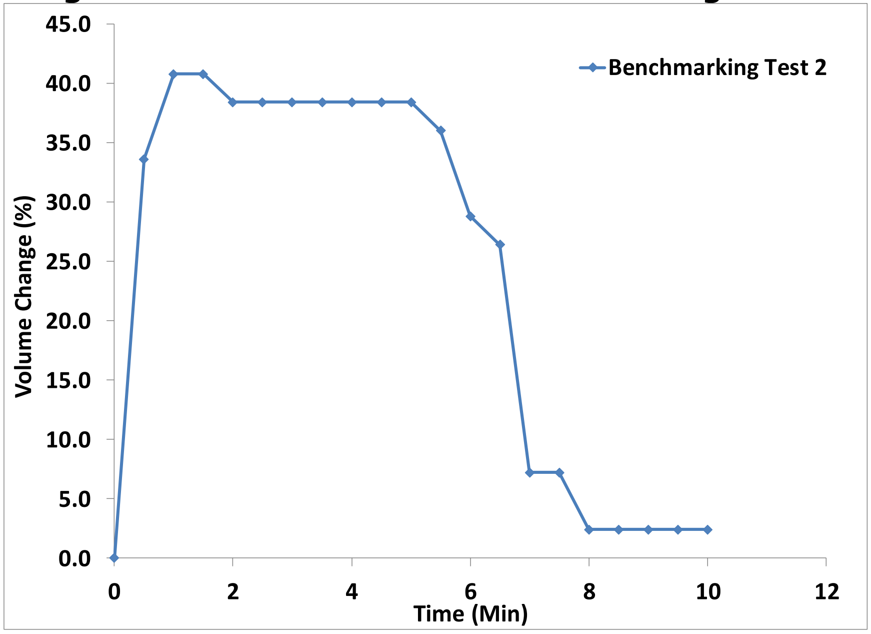
The RVE for Test 1 and Test 2 was measured in the lab. Figure 24 and Figure 25 summarize the results from these measurements, which signify the change in volume due to foaming and gas holdup (Higgins et al. 2014). The tests are shown in separate figures due to the varying time periods the tests were conducted.

Figure 24: RVE for Benchmarking Test 1



Source: Kennedy/Jenks Consultants

Figure 25: RVE Potential for Benchmarking Test 2



Source: Kennedy/Jenks Consultants

This percent volume change was less than 6 percent for Benchmarking Test 1, which was measured after 1000 minutes (Figure 24). The length of the tests is variable and depended upon when the digester solids reached their peak and began to collapse. In this case, the foam only fell to the zero marking after this long duration, though the volume change was small. In Benchmarking Test 2, the changes in the sludge volume during mixing was higher, about 42 percent (Figure 25). This signified a higher RVE potential and was in accordance to actual conditions of foaming periods in Digester 2.

4.2.9 Zeta Potential

Zeta potential (ZP) provides useful indirect information in determining the polymer demand. One of the main mechanisms of coagulation/flocculation is charge neutralization, which can be deduced from ZP. For example, the more negative the ZP, the more polymer is needed for charge neutralization. 2.

Table 24 summarizes the ZP values measured for the sludge feed (TPS and TWAS) and the digester sludge during Test 1 and Test 2.

Table 24: Zeta Potential of Feed and Dig 2 Contents

Samples	Benchmarking Test 1 Zeta Potential (mV)	Benchmarking Test 2 Zeta Potential (mV)
PS	–21.9	–21.4
TWAS	–23.3	–23.5
Dig 2	–29.1	–29.0

Source: Kennedy/Jenks Consultants

The measured ZP values were all very similar for both the feed and digester sludge across the two benchmarking tests. However, the OPDs used during each test varied significantly.

Therefore, while ZP can be a useful indicator for determining polymer demand, other factors may be at play.

4.3 Summary of Benchmarking Tests

This section evaluated the benchmarking data on gas production, dewatering, solids production, viscosity, foaming or volume expansion, and cake quality in terms of odors, when no codigestion was carried out. The following are the main findings of this work:

1. Gas production increased as expected with sludge loading. The VS reduction also increased with the increased loading. The unit gas production decreased from about 15 to 13 cu.ft. gas produced/lb VSR in benchmarking tests. The lower unit gas production in Benchmarking Test 2 may be due to the change in digester mixing pattern, which was implemented during the test period.
2. Methane content in biogas increased in Benchmarking Test 2.
3. The amount of H_2S in biogas increased five times in Test 2. This is primarily attributed to reduced ferric chloride dosing at the plant.
4. The optimum polymer dose for Test 2 (35 lb/DT of solids) was higher than that of Test 1 (28 lb/DT of solids). However, the dewatered cake percent solids improved by approximately 1.5 percent at the higher sludge loading test. The increased polymer demand in Test 2 could be attributed to reasons such as mixing pattern change at increased loading and lowered ferric dosage during Benchmarking Test 2.
5. The production of cake odorants in Test 2 was generally higher than in Test 1.
6. Frequent rapid rise foam episodes in the digester correlated with increased volume expansion due to foaming and gas hold up.
7. The M/D ratio increased with increased VS in Test 2 and was in the range considered to be suitable for dewatering.

CHAPTER 5:
FOG Codigestion Strategy: Results and Discussion

The results from all the fats, oils, and grease (FOG) tests of the codigestion study are presented and discussed in this chapter. The results shown in each figure are the average values with the error bars depicting one standard deviation of the steady-state average data during each test. The percent differences (where presented) are based on comparisons to the corresponding benchmarking test, based on total VS loading.

5.1 Testing Approach

The testing approach was to add a targeted amount of FOG to the test digester until the digester reached steady-state operating conditions. This was tracked via gas production, VSR, and digester effluent VS percentage. After steady state was established, samples and data collection were initiated. As detailed in Chapter 3, this approach could not always be maintained because of limited FOG supply. Accordingly, the approach had to be modified during FOG tests 2 and 3. During the initial acclimation for these tests (that is, the weeks leading up to receiving the targeted loading), the test digester was operated at the targeted sludge VS loading, and any amount of FOG received was added to the digester to get the microorganisms partially acclimated to the test conditions. The percentage of sludge and FOG added to the digester for each test is outlined in Table 25.

Table 25: FOG Codigestion Strategy Approach

Test Timeline	Average Loading (lbs VS/ cu.ft.)[1] Sludge	Average Loading (lbs VS/ cu.ft.)[1] FOG	Average Loading (lbs VS/ cu.ft.)[1] Combined (Sludge + FOG)	Average FOG VS: Sludge VS (%)[1]	Average Volume of Sludge (GPD)[1]	Average Volume of FOG (GPD)[1]	Operation Variations
FOG Test 1 (12.5% FOG)	0.073	~0.01	~0.09	12.5	~46,000	~8,250	Digester mixing frequency reduced (6 hour on/off cycle for mixing).
FOG Test 2 (26% FOG)	0.08	~0.02	0.1	~26	~57,000	~12,000	Digester mixed 24/7. Reduced ferric chloride dosing. Steady state could not be verified because the targeted loading of FOG was received for a limited duration.
FOG Test 3 (48% FOG)	~0.07	~0.03	0.1	~48	41,500	~28,000	Digester mixed 24/7. Steady state could not be verified because the targeted loading of FOG was received for a limited duration.

Note: [1] Average over each test period

Source: Kennedy/Jenks Consultants

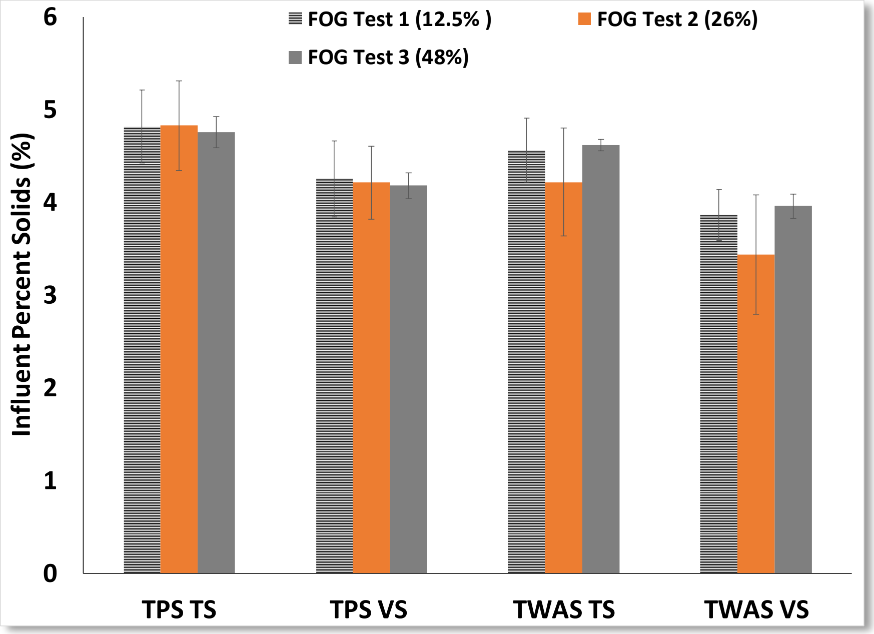
The target FOG loading (VS) for the three tests was 12.5, 26, and 48 percent of the sludge VS loading, respectively. The FOG and sludge VS loading were controlled based on these target values. During FOG Test 1, the utility continued to operate the digester at reduced mixing conditions (six-hour on/off cycles) to control foaming. Prior to FOG Test 2, digester mixing frequency was increased to continuous mixing (24/7). Changes in digester mixing frequency are important because mixing changes can affect gas production as well as sludge characteristics. Further, the utility experienced ferric chloride dosing problems, which reduced dosing rates significantly during FOG Test 2. Reduction in ferric chloride dose can affect H_2S concentrations in biogas, as observed during benchmark testing, as well as sludge dewatering characteristics.

5.2 FOG Tests – Results and Discussion

5.2.1 Influent Sludge Solids Content

The feed sludge characteristics varied during the project period due to changes in thickened primary sludge (TPS) and thickened waste-activated sludge (TWAS) quality that occurred over time. The average TS and VS values of the TPS or TWAS were measured during the three FOG tests as shown in Figure 26.

Figure 26: Average Daily Feed Sludge TS and VS for Each Test



Note: Error bars represent standard deviation.

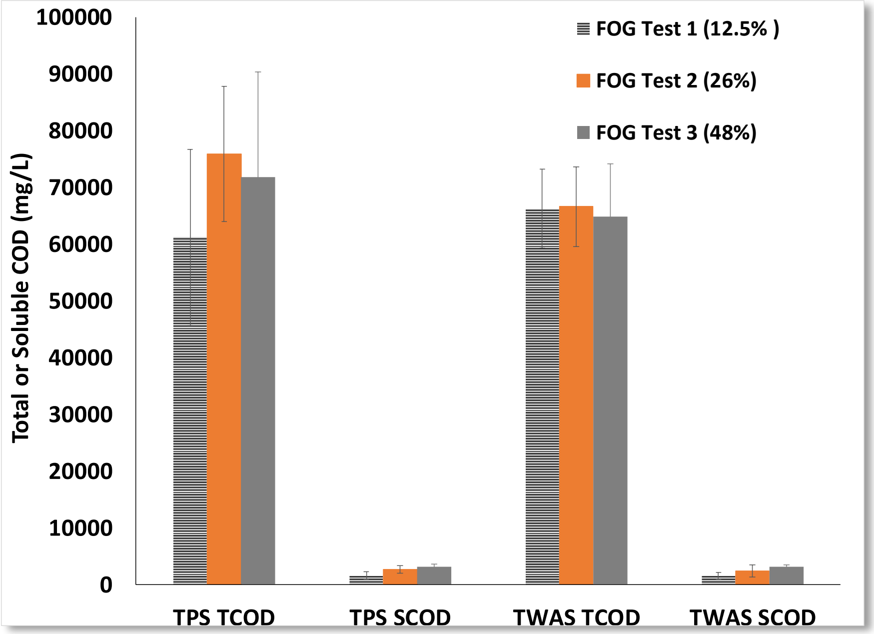
Source: Kennedy/Jenks Consultants

The TPS for all FOG tests had similar average TS (approximately 4.8 percent) and VS (approximately 4.2 percent) values. The TWAS solids were similar for FOG Test 1 and 3 (PS approximately 4.6 percent and VS approximately 3.8 percent) but was slightly lower for FOG Test 2 (PS approximately 4.2 percent and VS approximately 3.5 percent). The variation observed between different samples (standard deviation) was typical of the day-to-day changes in influent wastewater characteristics. The percent solids in the TPS feed could also vary depending on the operation of the gravity thickener. Overall, the percent solids of the feed sludge were similar to that observed during benchmarking tests.

5.2.2 Influent Sludge Solids COD

The total and soluble COD of the influent TPS and TWAS was measured for FOG tests 1, 2, and 3. The results from the COD analyses are shown in Figure 27.

Figure 27: Average Daily Influent Sludge Total and Soluble COD



Note: Error bars represent standard deviation.

Source: Kennedy/Jenks Consultants

The TPS influent total COD (TCOD) varied from approximately 61,000 mg/L to 75,000 mg/L. The TWAS TCOD was slightly lower but more consistent, varying between 64,000 and 67,000 mg/L. The COD variation observed in the influent feed sludge (TPS and TWAS) was largely due to the changes in feed characteristics coming in to the WWTP. The TPS TCOD in FOG Test 1 was 24 percent less than the TPS COD of FOG Test 2 and 17.5 percent less than in Test 3. The soluble chemical oxygen demand (sCOD)of FOG Test 3 was almost twice that of FOG Test 1. Such changes in feed COD are considered to be related to normal variation of the influent. Feed sludge TCOD values in literature have reported a similar wide range of values (Wentzel, Ekama, et al. 2006). The total and soluble COD values were similar to those obtained during the benchmarking tests discussed in Section 4.2.2.

5.2.3 Feed FOG Characteristics

The FOG waste received was sampled daily or over multiple loads during this study and was characterized along with influent sludge. Results from these characterizations are discussed in the next section.

5.2.3.1 Variation in Received FOG Quantity and Quality

The FOG volume, TS percentage, VS percentage, and TCOD were measured during the time leading to each FOG test and the test period itself to monitor the quality of the FOG and to determine the FOG loading rates to the digester. Table 26 summarizes the analyses performed prior to FOG Test 2 to illustrate the observed variations in quantity and quality of the FOG received.

Table 26: FOG Characteristics During Steady State Evaluation Prior to FOG Test 2

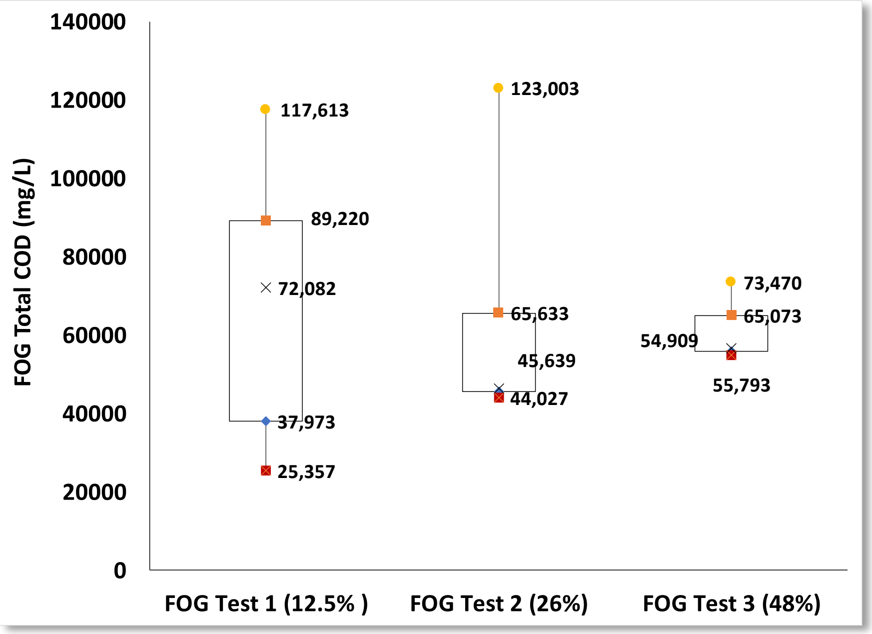
Parameter	Range of Values (Median)
Quantity of FOG received (gpd)	1,160–27,400 (4,714)
TS (%)	1–14.2 (2.0)
VS/TS Ratio	0.75–0.97 (0.93)
TCOD (mg/L)	7,970–110,000 (57,500)

gpd: gallons per day

Source: Kennedy/Jenks Consultants

The quantity of FOG received daily at SVCW varied significantly, ranging from 1,160 gallons per day (gpd) to 27,400 gpd. Similarly, the quality of the FOG also varied widely, with TS percent ranging from 1 to 14 percent and TCOD concentrations ranging from 8,000 mg/L to 110,000 mg/L. Similar or higher variations were observed during the time leading to FOG Test 3 as well. The variation in TCOD for the received FOG loads during the three FOG tests is further illustrated by the data presented in Figure 28.

Figure 28: Box Plot of TCOD Variation in Received FOG Loads

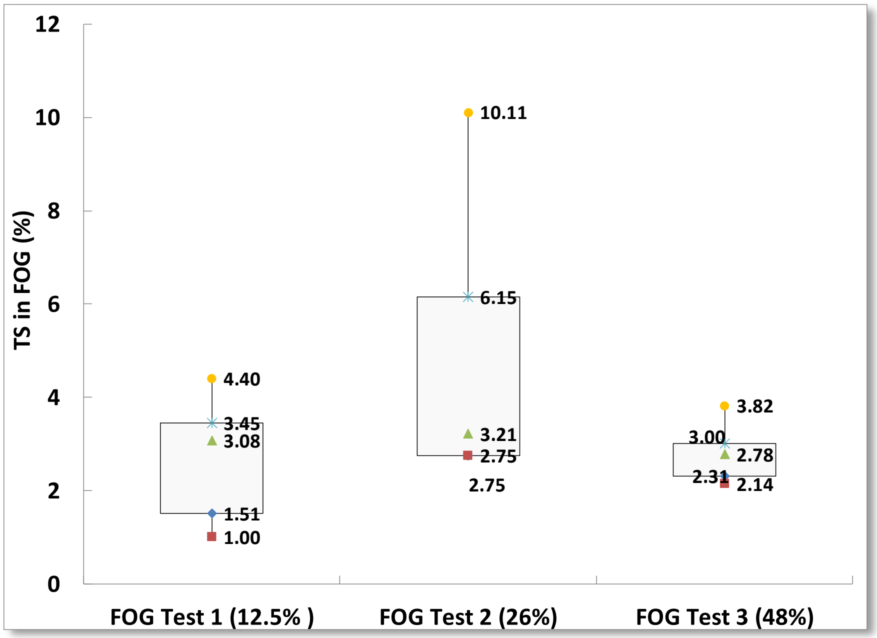


Note: The bounds of the box represent the upper and lower 25th percentile of the data; the band through the box represents the median, while the error bars or whiskers represent the minimum and maximum values for the entire range of the data.

Source: Kennedy/Jenks Consultants

FOG Test 1 had the highest average TCOD concentration (72,000 mg/L) and the largest variation in TCOD concentration (25,000 mg/L to 117,000 mg/L) (Figure 28). The variation in TCOD concentration was also high for FOG Test 2 (44,000 mg/L to 123,000 mg/L). FOG Test 3 exhibited a narrower range in TCOD (55,800 mg/L to 73,500 mg/L). The lower variability in the FOG TCOD quality during FOG Test 3 was likely due to the lower number of deliveries and samples made during the shorter testing period. The variation in TS percentage and VS percentage for the received FOG loads during the three FOG tests is further illustrated by the data presented in Figure 29 and Figure 30 respectively.

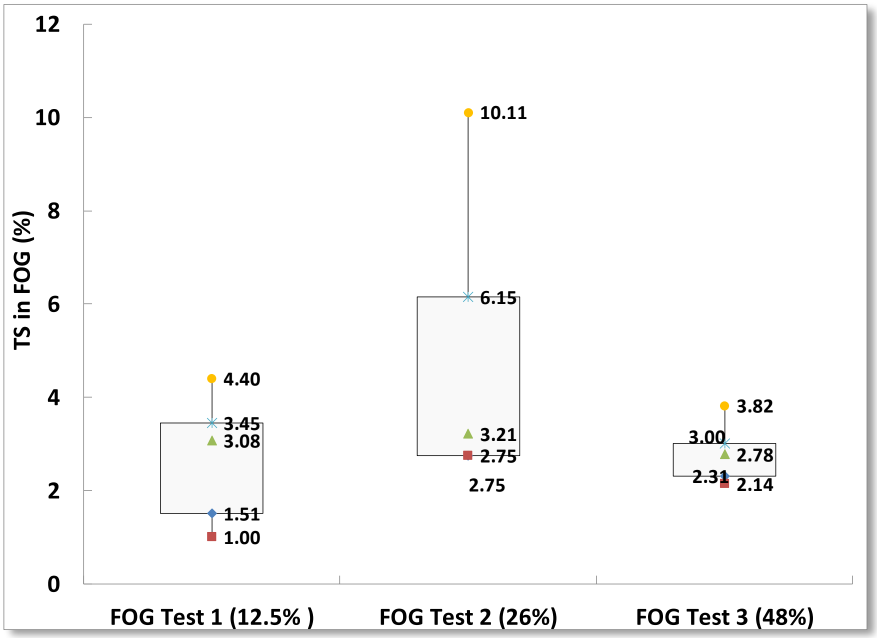
Figure 29: Box Plot of TS Percentage Variation During the FOG Tests



Note: In these plots, the bounds of the box represent the upper and lower 25th percentile of the data; the band through the box represents the median, while the error bars or whiskers represent the minimum and maximum values for the entire range of the data.

Source: Kennedy/Jenks Consultants

Figure 30: Box Plot of VS Percentage Variation During the FOG Tests



Note: In these plots, the bounds of the box represent the upper and lower 25th percentile of the data; the band through the box represents the median, while the error bars or whiskers represent the minimum and maximum values for the entire range of the data.

Source: Kennedy/Jenks Consultants

FOG Test 2 had the highest average TS and VS concentration (3.21 and 3.05 percent respectively) and the largest sample variation (2.75 to 10.11 percent TS and 2.35 to 9.89 percent VS) (Figure 29 and Figure 30). The variation in both TS and VS percentage for FOG Test 1 was less. FOG Test 3 exhibited the most consistent values for TS and VS percentages, but this may be attributed to the lower number of samples received.

The received FOG loads mainly consisted of grease trap waste (GTW). The observed variations in the FOG quality were discussed with the FOG hauling companies and SVCW operating staff. Through these discussions, the variability was attributed to the following:

- Sources of FOG: In the kitchens of commercial establishments, such as cafes, fast food joints, restaurants, delis, grocery stores, and others, the kitchen wastewater goes through the grease traps before entering the main sewer lines. The grease trap prevents FOG and other food solids from getting into the sewer system. Most haulers use water jets to clear all the grease out of these traps. This potentially dilutes the FOG more at source. Typically, restaurant/fast food joints are sources of concentrated FOG, and delis and grocery stores produce more diluted FOG, as they have less food processing and cooking activity.
- Type of FOG flushing: The type of FOG trap clearing equipment and consequently the methods haulers use to flush the FOG traps affect quality. Newer, modern hauling trucks are more effective in getting all the grease solids and grease out. Sometimes for larger traps or based on contract specifications, haulers only tend to remove the FOG floating on the surface of the trap thus leaving the settled FOG solids behind.

- Seasonal variations: Oil and grease tend to solidify in colder temperatures, making it harder to remove and thus requiring more water. This may have been a factor during FOG Test 2, which was conducted in January. The steady state tracking period and the time of the test experienced lower temperatures than the other two tests, which were conducted in August and May.
- Losses during flushing and transport: There are losses of grease during clearing of traps, transport, and FOG storage that cannot be quantified and cause additional variation.

Due to these reasons, FOG quality could not be controlled during the tests and subsequently, steady state could not be verified for the higher loading FOG tests (Test 2 and Test 3).

5.2.3.2 Other Feed Sludge and FOG Characteristics

In addition to TCOD, TS percentage, and VS percentage, other constituents in the digester feed could have affected digester performance. Table 27 shows the levels of some of these constituents in the TPS, TWAS, and FOG influent.

Table 27: Representative Characteristics of Feed Sludge and FOG

Parameter	TPS	TWAS	FOG
Carbon : Hydrogen : Nitrogen (CHN)[1] (%)	47.6 : 7.2: 3.3	42.06 : 6.7 : 7.6	63.8 : 9.7 : 2.5
pH	6.0	6.3	4.9 ±0.3
Electrical Conductivity (mS/cm)	2.1 ± 0.04	2.6 ± 0.14	2 ± 1.2
Ammonia-N,(mg/L NH_4-N)	213 ± 19	327 ± 75	119 ± 52

[1] **Average from FOG Test 1 and 3; FOG Test 2 data N/A; otherwise all others are average values from all FOG tests.**

Source: Kennedy/Jenks Consultants

CHN content during the FOG tests did not vary significantly from that of the benchmarking tests (Section 4.2.2) as well as other codigestion studies in literature, in which the values vary between 44 and 49 percent C, 6 and 8 percent H, and 2and 4 percent N for TPS and between 39 and 42 percent C, 6 and 7 percent H, and 7and 8 percent N for TWAS (Higgins and Rajagopalan 2017). Similarly, the FOG CHN content (64 percent C, 10 percent H, 2.5 percent N) was in the range (53 to 67 percent C, 8 to 11 percent H, and 0.2 to 2.4 percent N) reported in the literature, despite the varying sources and quality (Higgins and Rajagopalan 2017). FOG typically has a lower nitrogen content because it is not a source of protein as compared to other wastes such as food and animal wastes (Long, Aziz, et al. 2012).

The pH of the feed sludge was in a normal range and did not vary considerably from that of the benchmarking tests (Section 4.2.2). FOG pH (approximately 5) was more acidic than the feed sludge (approximately 6) and was in similar ranges from other studies in literature (Higgins and Rajagopalan 2017; Long, Aziz, et al. 2012). The results of FOG feeding to the digester induced only a slight decrease in pH from 7.5 to 7.2 between FOG tests 1 and 3 (Section 5.2.6).

Electrical conductivity of the feed sludge did not vary significantly over time and was similar to the values exhibited during the benchmarking tests (Section 4.2.2). The conductivity of FOG samples exhibited higher deviations during this period.

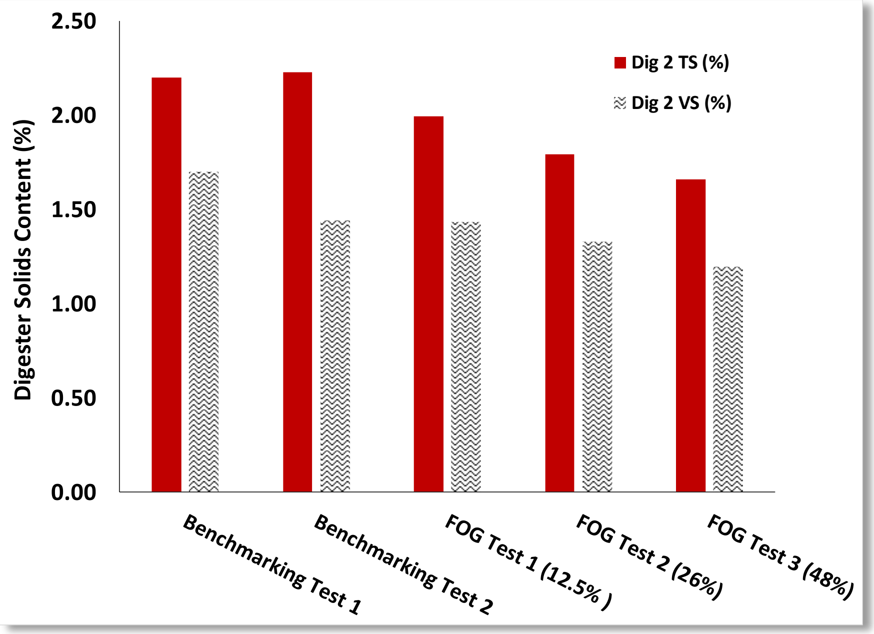
Typically, ammonia concentration in the feed at SVCW is subject to diurnal and weekday variations corresponding to changes in incoming plant flows. Ammonia concentration in FOG indicates that it is about 35 to 50 percent of that in TPS or TWAS sludges. Typically, FOG does not contain ammonia but since the sources vary significantly, there is potential for contamination. Such lower N concentration in the FOG could balance out the higher N concentration in some feed sludges and reduce the potential for ammonia toxicity.

5.2.4 Digester Performance – Solids, Total Gas Production, VSR, and Unit Gas Production

5.2.4.1 Digester Solids

The digester effluent TS and VS concentrations were measured for different FOG tests and compared to those obtained during the benchmarking tests (Figure 31). The TS and VS concentrations in the influent TPS, TWAS, and received FOG were also measured. Using the method adopted in Higgins et al. (2017), a mass balance on the test digester was conducted, assuming a 61 percent VSR for the sludge (based on historical VSR information from the plant). The incoming feed TS and VS values used for the analyses was the average of TPS, TWAS, and FOG values over the days of each test. The results from these analyses were used to calculate the FOG VSR and are summarized in Table 28.

Figure 31: Average Daily TS and VS in the Digester



Source: Kennedy/Jenks Consultants

The TS content for the digester during FOG tests 1, 2, and 3 were 1.97 percent, 1.79 percent, and 1.66 percent, respectively. The digester VS during FOG tests 1, 2, and 3 were 1.41 percent, 1.33 percent, and 1.20 percent, respectively. These results demonstrate a trend of TS and VS reduction with increasing FOG content. For example, FOG Test 3 (48 percent FOG) achieved an 18 percent reduction in TS and an 11 percent reduction in VS compared to FOG Test 1 (12.5 percent FOG). When compared to Benchmarking Test 2, the TS for FOG tests 2 and 3 were 20 percent and 26 percent lower, and the VS was 8 percent and 17 percent lower, respectively.

Table 28: Summary of Feed Sludge, Digester Solids, and Calculated VSR During FOG Testing

Test	Influent Sludge VS (lb/d)	Influent FOG VS (lb/d)	Feed FOG VS/TS Ratio	Feed Sludge VS/TS Ratio	Effluent VS/TS Ratio	Calculated FOG VSR (%)
FOG Test 1 (12.5% FOG)	15,542	1,943	0.92	0.87	0.72	65
FOG Test 2 (26% FOG)	16,075	4,180	0.97	0.83	0.74	69
FOG Test 3 (48% FOG)	14,936	~6,000	0.95	0.87	0.72	88

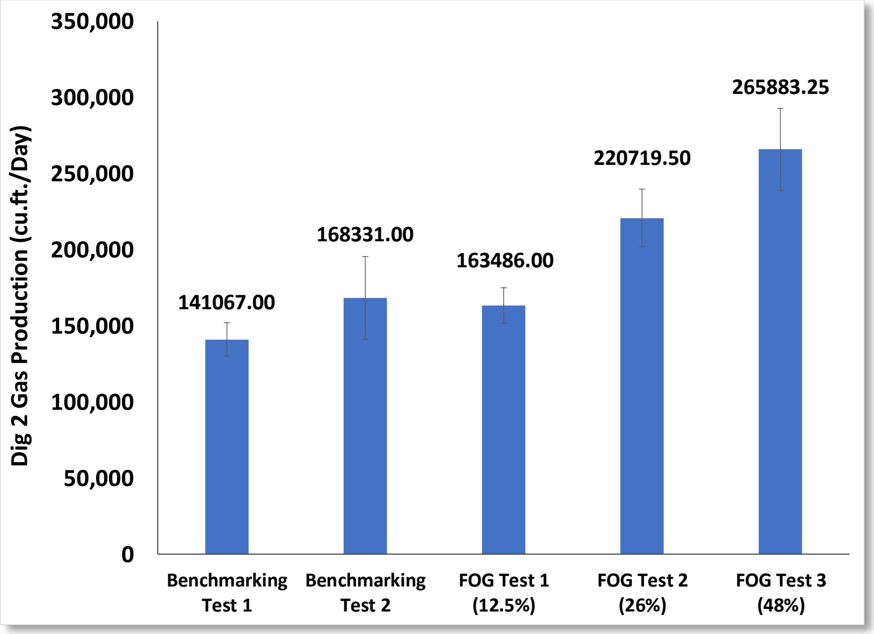
Source: Kennedy/Jenks Consultants

The FOG VS load during FOG tests 1, 2, and 3 was 1,943 lb VS/d, 4,180 lb VS/d and 6,000 lb VS/d, respectively. The VSR attributed to FOG also increased between each test. The VSR of the FOG stream was calculated to be 65 percent during FOG Test 1, 69 percent for FOG Test 2, and 88 percent for FOG Test 3. Published literature values for VSR of high strength waste range from 75 to 99.6 percent during codigestion in well-acclimated digesters (Higgins and Rajagopalan 2017). The digester had equivalent VS/TS loading during all the FOG tests (approximately 0.86), but the VSR increased with higher FOG loadings.

5.2.4.2 Total Gas Production, VS Reduction, and Unit Gas Production

The average daily gas flow measured during the FOG tests are presented in Error! Reference source not found.. Results from the benchmarking tests have been included for comparison. The feed volumes of sludge, FOG, corresponding feed VS, and the percent increase in total gas are given in Table 29. The gas production was compared with Benchmarking Test 2, whose VS loading was similar to the combined (sludge + FOG) loading of the FOG tests.

Figure 32: Increasing Gas Production with FOG Feed



Error bars represent standard deviation.

Source: Kennedy/Jenks Consultants

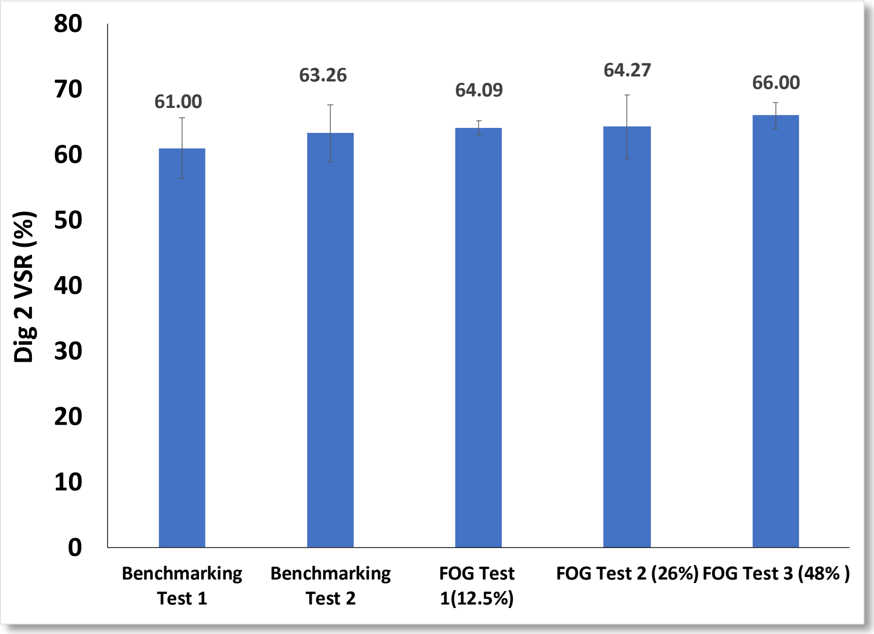
Table 29: Volumes of Sludge and FOG Fed and Total Gas Production

Test	Volumes of Feed Sludge Fed (GPD)	Influent Sludge and FOG VS (lb/d)	Influent FOG Volume: Sludge Volume	Influent FOG VS (lb/d)	Total Gas Production (cu.ft./day)	Difference in Gas Prod. from Benchmarking Test 2 (%)
Benchmarking Test 2 (0.11 lbs VS/cu.ft.)	~70,000	22,535	—	—	168,331	—
FOG Test 1 (12.5% FOG)	S: 45,600 F: 8,250	17,485	0.18	1943	163,486	3 (decrease)
FOG Test 2 (26% FOG)	S: 57,000 F: ~12,800	20,255	0.22	4180	217,283	29 (increase)
FOG Test 3 (48% FOG)	S: 41,500 F: ~28,000	20,936	0.67	6000	265,883	58 (increase)

Source: Kennedy/Jenks Consultants

Figure 33 shows the total gas production per day for each test. The total biogas production in FOG Test 3 was 265,883 cu. ft/day. FOG Test 2 produced 220,719 cu. ft/day of biogas, and FOG Test 1 produced 163,057 cu.ft/day. The last two FOG tests (FOG Test 2 and Test 3) had similar total flow (approximately 70,000 GPD) to Benchmarking Test 2, but received less sludge and lower influent VS. However, the total biogas production in these tests was significantly higher than that in Benchmarking Test 2. FOG Test 2 had a 29 percent increase in gas production compared to the Benchmarking Test 2, while FOG Test 3 showed a 58 percent increase. Gas production during FOG Test 1 was 3 percent lower than the benchmark, but still comparable. The lower biogas production in FOG Test 1 may be attributed to the lower feed flow or lower VS loading, but also the reduced mixing in the digester during FOG Test 1 (six-hour mixing cycles versus 24/7 continuous mixing). The comparison of the gas production data among all these tests indicates that that addition of FOG significantly increased biogas production potential.

Figure 33: VSR of FOG and Benchmarking Tests



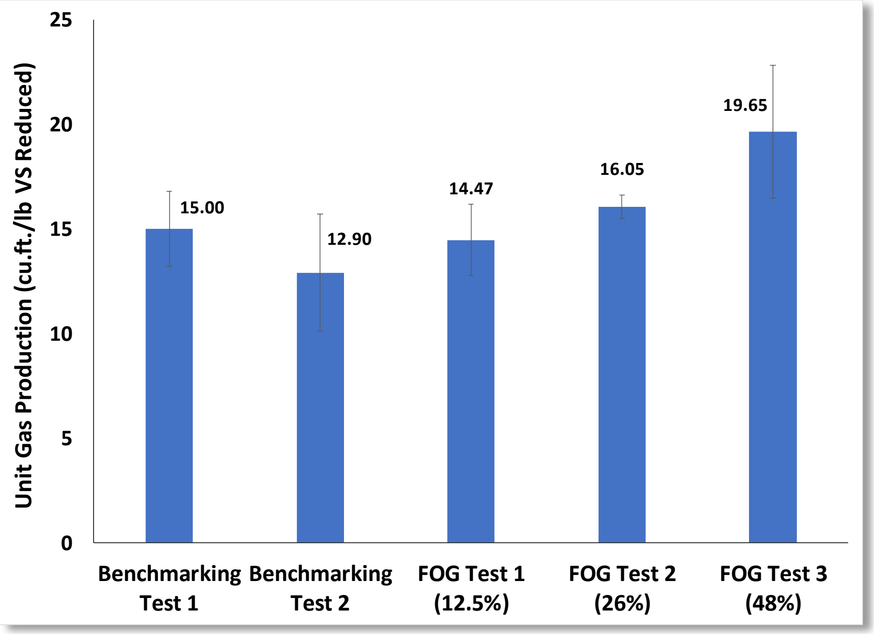
Error bars represent standard deviation.

Source: Kennedy/Jenks Consultants

The VSR in the digester increased with an increase in FOG addition (Figure 33). VSR in the two benchmarking tests was approximately 61 percent and approximately 63.3 percent, respectively. The VSR in the three FOG tests was higher than 64 percent, with an increase in the percentage of VSR as the percentage of FOG increased. This additional VSR during the FOG tests can be explained by the increasing ratio of VS from FOG in the digester feed, as well as possible synergistic effects of codigestion (Higgins and Rajagopalan 2017).

The unit gas production normalized for VSR for all the tests is shown in Figure 34. This parameter is also known as specific yield or the unit gas production per pound of VS destroyed (that is cu. ft/day/lb VS reduced).

Figure 34: Unit Gas Production for All FOG Tests



Error bars represent standard deviation.

Source: Kennedy/Jenks Consultants

The unit gas production increased with the increase in the percentage of FOG VS added. The unit gas production for FOG Test 3 was 36 percent higher than that for FOG Test 1. Further, Benchmarking Test 2 and FOG Test 3 received almost similar VS loading. However, the unit gas production from FOG Test 3 was 52 percent higher than that from Benchmarking Test 2. In the lower loading FOG Tests (FOG tests 1 and 2), this increase was 12 percent and 24 percent, respectively. These data indicated that for the same VS loading, codigestion of FOG produced more biogas than that produced by only sludge.

5.2.5 Gas Quality

This section discusses the quantity and quality of the raw biogas generated in the digester.

5.2.5.1 Methane and CO_2 Content

The two primary constituents of biogas from anaerobic digestion are methane and CO_2. Typical concentrations of methane and CO_2 in digester gas generated from anaerobic digestion of sludge (TPS and TWAS) are between 60 and 65 percent and 30 and 35 percent, respectively, along with trace amounts of H_2, N_2, H_2S, and H_2O. Codigestion of high energy wastes such as FOG have been shown to increase the methane and reduce the CO_2 content of the gas, which is beneficial for increased energy generation. The methane and CO_2 content of the digester gas generated during the benchmarking and FOG tests was measured and the results are summarized in Table 30.

Table 30: Methane Content and Methane Production in the FOG Tests

Test	Biogas Production (cu.ft./day)	Methane Content (%)	Average Methane Production (cu.ft./day)	CO_2 Content (%)
Benchmarking Test 1 (0.07 lbs/cu.ft.)	141,067	59.5	83,934	35.2
Benchmarking Test 2 (0.11 lbs/cu.ft.)	168,331	62.8	105,712	36.5
FOG Test 1 (12.5%)	163,486	60.2	98,418	38.9
FOG Test 2 (26%)	220,719	60.5	133,535	37.3
FOG Test 3 (48%)	265,883	66.9	177,875	32.9

Source: Kennedy/Jenks Consultants

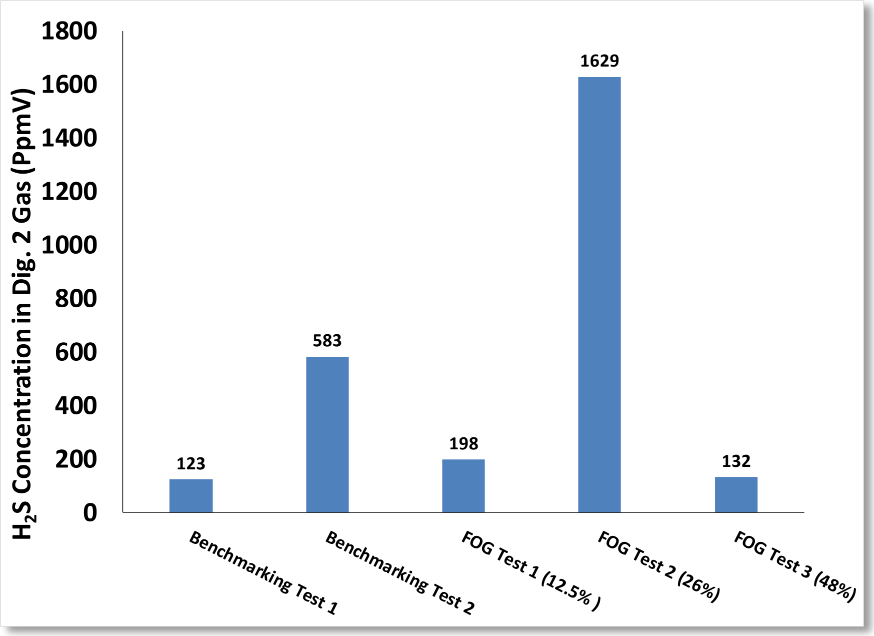
The methane content of the gas generated during FOG Test 1 and Test 2 was similar (60.2 and 60.5 percent). FOG Test 3, which had the highest FOG loading, had the highest methane content (approximately 66.9 percent). The CO_2 content decreased from approximately 39 percent in FOG Test 1 to approximately 33 percent in FOG Test 3. Fats, greases, and lipids, which are typical constituents of FOG, have the potential of being converted into biogas with a methane content of 66 to 73 percent (Long, Aziz, et al. 2012). The observed methane content from FOG Test 3 was higher than other protein and carbohydrate-rich sources that produce a biogas with only 50 to 58 percent methane contents (Long, Aziz, et al. 2012).

The total biogas and methane production in FOG tests 2 and 3 were much higher than that of Benchmarking Test 2, even though Benchmarking Test 2 received equal or higher VS loading as the FOG tests. This is further evidence that the addition of a higher loading of FOG VS enhanced methane content in the biogas compared to the addition of sludge VS.

5.2.5.2 H_2S Production in the Digester

After methane and CO_2, H_2S may be the next most commonly occurring constituent of biogas produced during anaerobic digestion (Kuo and Dow 2017). H_2S is formed in the anaerobic digester by sulfate reducing bacteria and causes a variety of issues. It is odorous and causes corrosion of engines and other equipment by release of acidic sulfur dioxide during combustion. It is also highly toxic. The amount of H_2S formed during digestion is dependent on the substrate fed to the digester, the digester chemistry, and addition of coagulants such as ferric salts to the digester. The digester gas was measured for H_2S during the current study to determine if FOG addition changed the H_2S concentration of the gas. The H_2S concentration measured during the benchmarking and FOG tests is provided in Figure 35.

Figure 35: Variation in H_2S Concentrations Measured During Benchmarking and FOG Tests



Source: Kennedy/Jenks Consultants

As illustrated in Figure 35, the H_2S level in FOG Test 2 was almost an order of magnitude higher compared to FOG Tests 1 and 3. This can be attributed to the treatment plant having ferric chloride pumping and dosing issues during this period. Iron salts such as ferric chloride bind with the sulfides and prevent its release. The reduced ferric chloride dosing likely resulted in higher H_2S concentration during FOG Test 2. The ferric chloride feed pump was fixed prior to the start of FOG Test 3 and the H_2S concentrations in FOG Test 3 returned to similar (lower) levels as FOG Test 1. This suggested that the higher H_2S levels in the digester gas during FOG Test 2 was not related to increased FOG feed. Problems with ferric chloride dosing were experienced during Benchmarking Test 2 also. As a result, H_2S levels had increased in the biogas during that test as well.

5.2.6 pH, Alkalinity and VA in Digester

The performance of a digester was generally determined based on the VSR and gas production. However, the digester chemistry was an equally important indicator of the digester stability. Digester chemistry constitutes pH, alkalinity, and volatile acid (VA) concentration and it is important that they are in the appropriate range to ensure proper and stable digester operation. Table 31 compares the pH, alkalinity, and VA values measured during the benchmarking and FOG tests.

Table 31: Digester pH, Alkalinity, and VA

Test	pH	Alkalinity (mg/L)	VA (mg/L)	VA/A Ratio
Benchmarking Test 1	7.5 ± 0.02	4600	N/A	0.07
Benchmarking Test 2	7.7 ± 0.1	4575	N/A	0.06
FOG Test 1 (12.5%)	7.5 ± 0.02	3900	240	0.06
FOG Test 2 (26%)	7.5 ± 0.4	4015	190	0.05
FOG Test 3 (48%)	7.2 ± 0.1	3150	138	0.04

Notes: All VA and alkalinity analyses conducted by SVCW laboratory.

Source: Kennedy/Jenks Consultants

The pH was within acceptable operations range in all the tests. Even though the pH of FOG itself is approximately 4.9, the digester remained at a pH of 6.8 or greater. Addition of FOG can decrease the digester pH as the loading rate increases and a significant drop can lead to digester stability issues. Such an occurrence was not observed at the loading used in these tests. The digester pH did not drop significantly even at the highest FOG loading, indicating the digester was well buffered during the tests. When compared to the benchmarking tests, addition of FOG did not have an overall effect on the digester pH.

The alkalinity increased marginally (approximately 3 percent) during FOG Test 2 compared to FOG Test 1. Alkalinity decreased as expected with FOG addition (32 percent decrease in FOG Test 3 compared to Benchmarking Test 2). The values were 3150 mg/L and 4600 mg/L respectively. Typically, addition of FOG to digesters also lowers the alkalinity (Higgins and Rajagopalan 2017).

In general, VA decreased with an increase in FOG loading, and the VA/A ratios exhibited a decrease during FOG tests 2 and 3, when compared to Benchmarking Test 2. The VA/A ratios were all below 0.10, which is often considered a threshold level for stable operation (Wan et al. 2011). High VA concentrations tend to have toxic effects and the resulting drop in pH causes inhibition (Trzcinski and Stuckey 2018).

5.2.7 Dewatering and Odor Tests

Dewatering of the digested sludge with FOG addition over three tests was performed at bench scale in Bucknell University in the same way as that of the benchmarking tests. The following parameters were determined during the dewatering experiments:

- Optimum polymer dose (OPD)
- Digester sludge TS
- Percent TS of the dewatered cake: an estimate of the net mass of cake generated (that is, mass of sludge requiring disposal)
- Odor production from dewatered cake: Total volatile organic sulfur compounds (TVOSC), such as methyl mercaptan (MT) and dimethyl sulfide (DMS).

5.2.7.1 Optimum Polymer Dose

The OPD was determined using the capillary suction time (CST) curves, based on bench-scale tests performed using the same polymer. The comparison of the OPD for the three tests is shown in Table 32 to determine the effect of FOG addition.

Table 32: Comparison of OPD for Each Test With Operational Considerations

Test	OPD (lbs/DT)	Mixing	Ferric Chloride Dosing	Other	Percent Difference in OPD from Benchmarking Test 2
Benchmarking Test 1 (0.07 lbs/cu.ft.)	28	Mixed 24/7.			
Benchmarking Test 2 (0.11 lbs/cu.ft.)	35	Dig 2 mixing pattern change.	Dosing issues (reduced ferric chloride)	Frequent rapid rise foam episodes	
FOG Test 1 (12.5%)	28.6	Reduced mixing (6hr cycles)		~5-week acclimation	18.3 (decrease)
FOG Test 2 (26%)	30.75	Mixed 24/7	Dosing issues (reduced ferric chloride)	Steady state could not be verified	12 (decrease)
FOG Test 3 (48%)	34.37	Mixed 24/7	Dosing returned to normal	Steady state could not be verified	1.8 (decrease)

Source: Kennedy/Jenks Consultants

Approximately 28 lb/DT of polymer was required for dewatering the digested sludge from FOG Test 1. In FOG Test 2, the dewatering did not improve as indicated by a higher OPD (approximately 31 lbs/DT) for dewatering. The OPD for Test 3 further increased to approximately 35 lb/DT. In addition to higher FOG loading several other factors could have contributed to the higher OPD in FOG Test 2 and Test 3. For example, the polymer demand for FOG Test 2 could have increased due to lower ferric chloride dosing. Ferric chloride helps condition the sludge and improve dewatering. In addition, insufficient acclimation time provided for FOG tests 2 and 3 could have caused the higher polymer demand.

In comparison with the benchmarking tests, the OPD for FOG Test 1 was comparable to Benchmarking Test 1. In the first FOG test, sufficient time for acclimation was provided. The polymer demand increased with increasing FOG feed. The OPD of FOG Test 3 was almost similar to that of Benchmarking Test 2 (both tests had a similar combined VS loading). The effect of FOG on polymer demand was potentially affected by the unverified steady-state conditions. In comparison to other codigestion studies in literature, polymer demand was generally higher for digesters fed with different high strength organic co-wastes compared to control digesters (Higgins and Rajagopalan 2017). In another full-scale study of about 25 percent FOG VS loading for codigestion, total polymer use was reported to decrease by 11 percent (York and Magner 2009).

5.2.7.2 Comparison With SVCW Full-Scale Polymer Demand

OPD data required for full-scale digester dewatering at SVCW was gathered to compare the values obtained from bench-scale dewatering tests. Large volumes of diluted FOG received over a short duration (about 50,000 gpd over three or four days) diluted the sludge considerably and plant operations suspected this diluted sludge was creating dewatering issues and consuming more polymer. Hence, two operating periods were monitored to assess the effect of FOG loading on OPD during full-scale operations: when relatively low loads of FOG were received, and when larger loads of FOG were received. The average FOG volume received during low FOG loading days and high FOG loading days (approximately 12 to 15 days of sampling each), and the maximum and average OPD used for the fan press during this period are shown in Table 33.

Table 33: OPD Use for Full-Scale Operation at SVCW With Addition of FOG

FOG Loading	Average FOG Received (GPD)	Average Sludge Received (GPD)	Average OPD (lbs/DT)[1]	Maximum OPD (lbs/DT)
Low FOG received	3,327	62,396	29.5 ± 6	40.4
Higher FOG received	11,176	59,755	44.5 ± 9	64.1

[1] **Average of the two fan presses.**

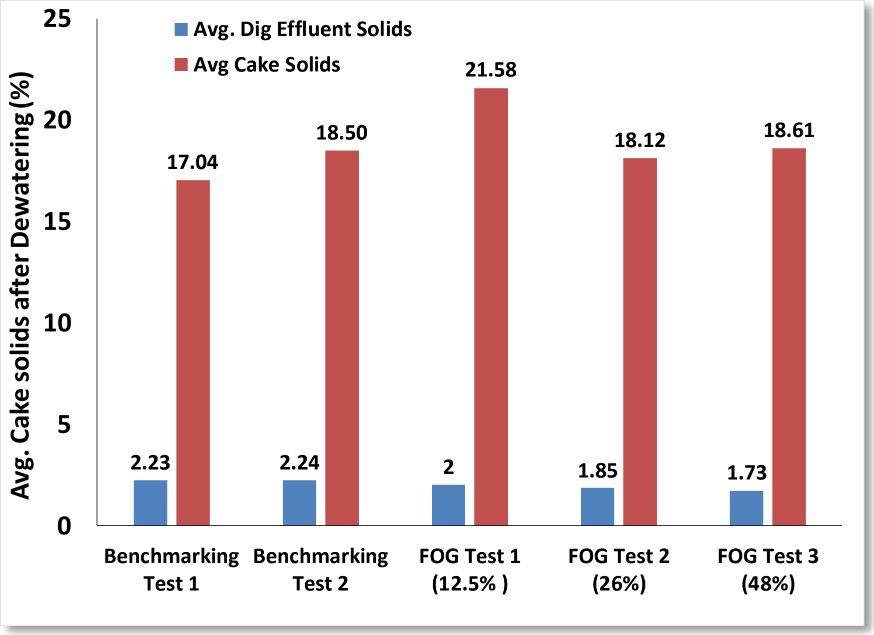
Source: Kennedy/Jenks Consultants

Polymer dosing for FOG loadings of 3,327 gallons per day was 29.5 lb/DT on average, while FOG loadings of 11,176 GPD (comparable to FOG Test 2) required 44.5 lb/DT on average. For these days, the volume of sludge received by the digester varied only by 5 percent (62,396 and 59,755 GPD). Full-scale OPD values were considerably higher than the OPD measured during bench-scale testing (ranging between 28 and 35 lb/DT). The full-scale and bench-scale tests for dewatering possess inherent differences due to dewatering equipment (fan presses in full-scale) and variation in the composition of the received sludge. In the full-scale plant at SVCW, the fan presses received digested sludge from Digester 3, which contained the digested effluent from Digester 2 (test digester), as well as FOG in excess of the target test loading and the remaining PS and TWAS sludge. This contrasts with the bench-scale dewatering tests, which received digested sludge exclusively from the test digester. Additionally, the CST data and thus the polymer demand used at the plant are operator dependent. Anecdotally, the plant operators may add extra polymer to ensure that the solids capture is maximized and to get the desired cake solids percentage. Hence, more polymer is potentially used than absolutely required (max OPD ranging between 40 and 64 lb/DT). Despite these variations, the trend observed for polymer demand increasing with FOG loadings was consistent between the full-scale operations and bench-scale dewatering tests.

5.2.7.3 Solids Dewatering

The dewatered solids content of the digesters is an indicator of the mass of sludge generated for hauling from the plant. An increase in percent solids in the dewatered cake represents a reduction in the mass of cake produced (and requiring disposal). The percent solids of the dewatered cake for each test is shown in Figure 36.

Figure 36: Average Cake Solids After Dewatering



Source: Kennedy/Jenks Consultants

The percent total solids in the dewatered cake from the two benchmarking studies were 17 and 18.5 percent, respectively. In FOG Test 1 (FOG VS approximately 12.5 percent of sludge VS) the dewatering efficiency improved to about 21.6 percent. Based on past research on full-scale codigestion studies, FOG addition was reported to improve dewatering (Higgins and Rajagopalan 2017). This 16.7 percent improvement in the cake solids between Benchmarking Test 2 and FOG Test 1 would typically result in approximately 15 to 16 percent reduction in dewatered cake mass requiring disposal (Higgins and Rajagopalan 2017).

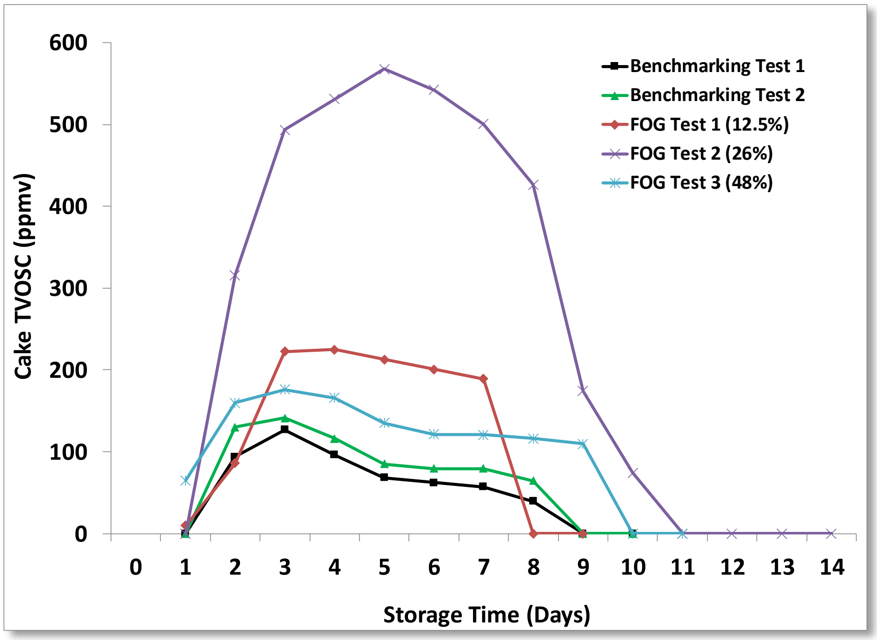
However, in FOG tests 2 and 3 the percent solids in the dewatered cake was lower than that for FOG Test 1. The percent solids for these two tests (approximately 18.5 percent) were comparable to the percent solids observed in the benchmarking tests, indicating that the change in cake requiring disposal may only be marginally different for FOG tests 2 and 3. When compared to other published full-scale studies, the codigestion of FOG with municipal sludge decreased the quantity of solids produced by 33 percent and improved biosolids dewaterability (York and Magner 2009).

Unlike FOG Test 1, where enough time (approximately five weeks) was allowed for the digester to acclimate to the FOG loading, FOG tests 2 and 3 were performed with minimal time for acclimation (one to two days). The lack of acclimation time may have affected the dewatering efficiency. Other possible factors, such as mixing efficiency associated with a larger volume of FOG addition, may have affected dewaterability as well.

5.2.7.4 Cake Odors Production

Compounds associated with the generation of odor are the total volatile organic sulfur compounds (TVOSCs) such as MT and DMS that act as surrogates for cake odors. Cake odors are an important biosolids quality aspect, especially in cases where utilities beneficially reuse their dewatered cake through land application (Novak 2006). Therefore, the effects of codigestion on cake odor are an important parameter to be evaluated. Figure 37 summarizes the TVOSC values measured for the dewatered cake during FOG testing.

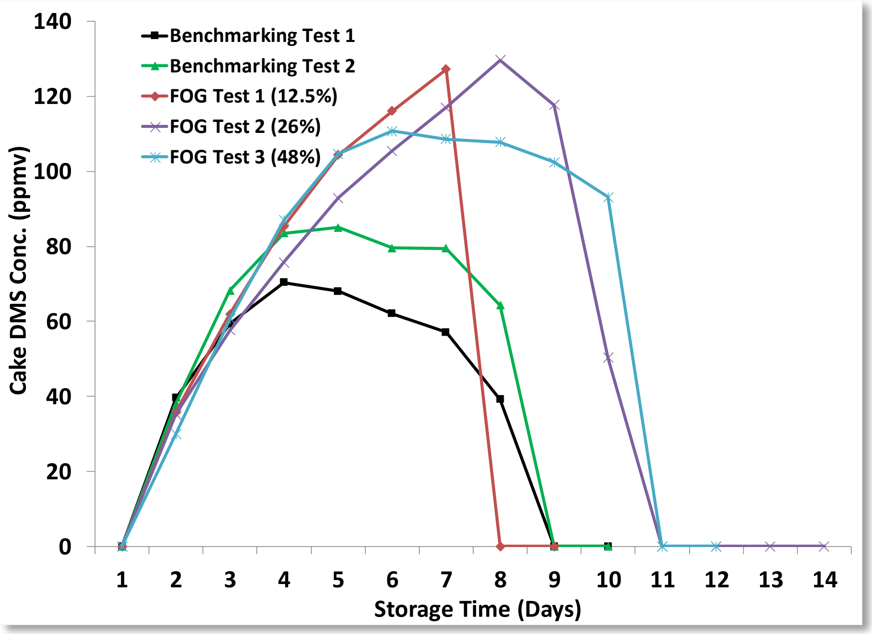
Figure 37: Peak Odor-Causing Compounds During Dewatered Cake Storage (TVOSC)



Source: Kennedy/Jenks Consultants

TVOSC concentrations were shown to be higher than those observed for benchmark tests. The peak TVOSC concentration for all FOG tests was approximately after five days of storage. The odor production of FOG Test 2 decreased to below detection levels after 11 days. Other FOG tests showed a similar but less dramatic trend, peaking at around 5 days of storage before dropping to below detection levels after 8 to 10 days. Figure 38 and Figure 39 show concentration levels of the individual odor-causing compounds DMS and MT, respectively.

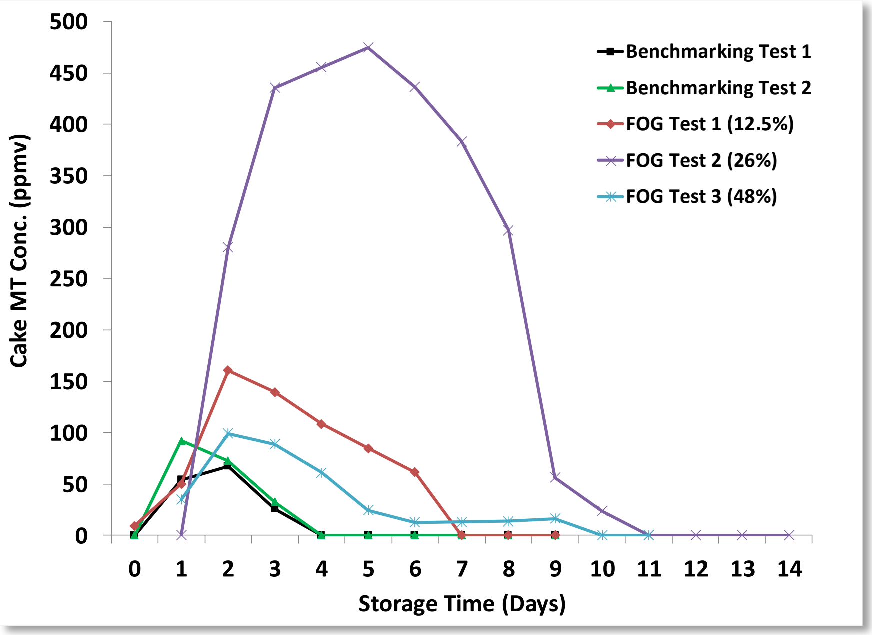
Figure 38: Peak Odor-Causing Compounds During Dewatered Cake Storage (DMS)



Source: Kennedy/Jenks Consultants

Unlike TVOSC trends, the peak DMS (a constituent of TVOSC) levels did not vary significantly at different FOG loadings. DMS exhibited a decrease with FOG Test 3 compared to FOG Test 2. FOG tests 1 and 2 concentrations were very similar (approximately 2 percent variation). However, the duration of the DMS emissions were two to three days longer for FOG tests 2 and 3. The DMS concentrations fell to below detection limits on day 9 for FOG Test 1 and day 11 for the other two FOG tests.

Figure 39: Peak Odor-Causing Compounds During Dewatered Cake Storage (MT)



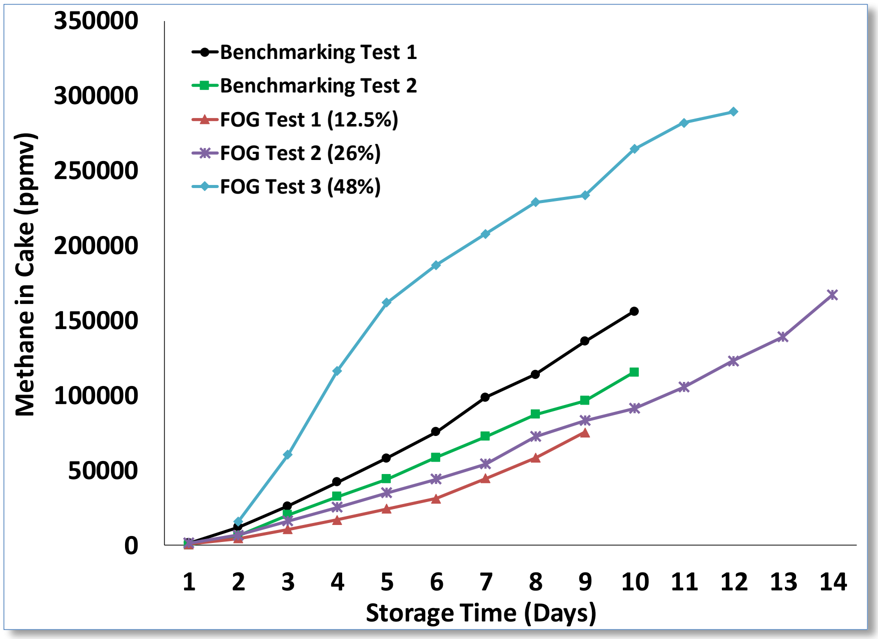
Source: Kennedy/Jenks Consultants

MT concentrations spiked about threefold in FOG Test 2 compared to FOG Test 1. It is possible that the problem associated with ferric chloride dosing during FOG Test 2 contributed to the higher MT levels. FOG Test 3 had the lowest MT concentrations of the three FOG tests, though all three had higher MT concentrations than the benchmark tests. MT concentrations dropped to below detection limits after 4 days for the benchmark tests and between days 7 and 11 for the three FOG tests. It is important to note that the odor-producing compounds (TVOSCs, DMS, and MT) all decreased in FOG Test 3, which received the highest FOG loading.

Similar odor (TVOSC or MT) trends such as this (that is, an increase in odor at lower amount of organic waste addition, followed by decrease in odor production at higher organic loading) were observed with several codigestion case studies of high strength waste (Higgins, Murthy, et al. 2002). This could possibly be the result of synergistic degradation of solids, which leads either more or less bioavailable materials, such as proteins, to accumulate in the cake. Protein in the cake has been shown to be related to cake odor production (Higgins, Murthy, et al. 2002) and could be a possible explanation for the variable odor trend observed.

In addition to synergistic degradation, reduction of odor-causing compounds by methanogens could also explain the decrease in odor production at higher organic loading. A higher methanogen activity will generally show a decrease in TVOSC production (Higgins, Murthy, et al. 2002). Determining the methane production profiles of the cake can help establish this degradation of cake odors. Figure 40 shows the methane concentration measured in the digester cake from each test.

Figure 40: Methane Concentrations in Cake



Source: Kennedy/Jenks Consultants

Methane concentration profiles of the cake solids show that the methane production increased with increasing addition of FOG. The methane production increased at the highest FOG loading in Test 3 and corresponded to the reduction observed in odor-causing compounds during that test. This indicated that methanogens played an important role in deactivating odor in this case of the highest FOG loading.

5.2.7.5 Cation Concentrations and M/D Ratio

Samples from each test were analyzed for soluble species of ammonium, sodium, potassium, calcium, and magnesium (Table 34) to study the effect of monovalent/divalent (M/D) cation ratio on dewatering.

Table 34: Cation Concentrations in Digester With FOG Addition

Species	Benchmarking Test 2	FOG Test 1	FOG Test 2	FOG Test 3
Calcium (mg/L)	**274**	**72**	**44**	**46**
Magnesium (mg/L)	**15**	**23**	**3**	**10**
Sodium (mg/L)	**214**	**214**	**211**	**215**
Potassium (mg/L)	**203**	**128**	**170**	**136**
Ammonium (mg/L)	**2023**	**1629**	**1482**	**1179**
Free Ammonia (mg/L)[1]	**71**	**57**	**52**	**41**

[1] Estimation based on Dig 2 pH in each corresponding test and temp of 35° C (95 °F).

Source: Kennedy/Jenks Consultants

It is unclear if there was a trend in the calcium and magnesium concentrations with increasing FOG load. The magnesium concentration increased between FOG tests 1 and 2 decreased between FOG tests 2 and 3, making it difficult to determine if there was a correlation between FOG loading and magnesium concentration. The calcium concentration appeared to be affected by the FOG load, as calcium concentrations decreased significantly (70 to 80 percent) between FOG tests 1 and 2 and remained low during FOG Test 3. In addition to the effect of adding FOG, several factors can affect the metal calcium concentrations, such as metal speciation and interaction of cations by the microorganisms. Most likely, calcium concentrations decreased with FOG due to the complexation/precipitation with carbonate alkalinity in the digester. Also, difference in the composition of FOG deliberated during each test may have caused differences in the concentrations obtained.

The sodium concentration in the digester was similar across all FOG tests. For potassium, the concentration increased between FOG tests 1 and 2, but declined between FOG tests 2 and 3 to a concentration more similar to FOG Test 1. The ammonia concentrations decreased with increasing FOG addition. This decrease was expected because FOG is not a significant source of nitrogen; although, the FOG in this study did have a slightly higher than expected nitrogen content (2.5 percent), likely due to comingling with other waste streams at the source. Higher ammonium concentrations have the potential to cause ammonia toxicity due to free ammonia. Based on the analysis for each test, the free ammonia concentrations are all below the toxicity range (80 to 150 mg N/L), suggesting that the ammonia will not cause inhibition during codigestion. The synergistic effects of the low nitrogen concentration in FOG when codigested with sludge can help in limiting the chances for ammonia toxicity.

5.2.7.6 Relationship Between M/D Ratio and Dewatering

Using the soluble cation concentrations from Table 34, the M/D ratio was calculated in milliequivalents per liter (meq/L). Table 35 shows the M/D ratio of the FOG tests, as well as the benchmarking tests for comparison.

Table 35: M/D Ratio Variation Over the FOG Tests

Test	M/D Ratio
Benchmarking Test 1	3.4
Benchmarking Test 2	8.5
FOG Test 1 (12.5%)	18.8
FOG Test 2 (26%)	39.2
FOG Test 3 (48%)	25.1

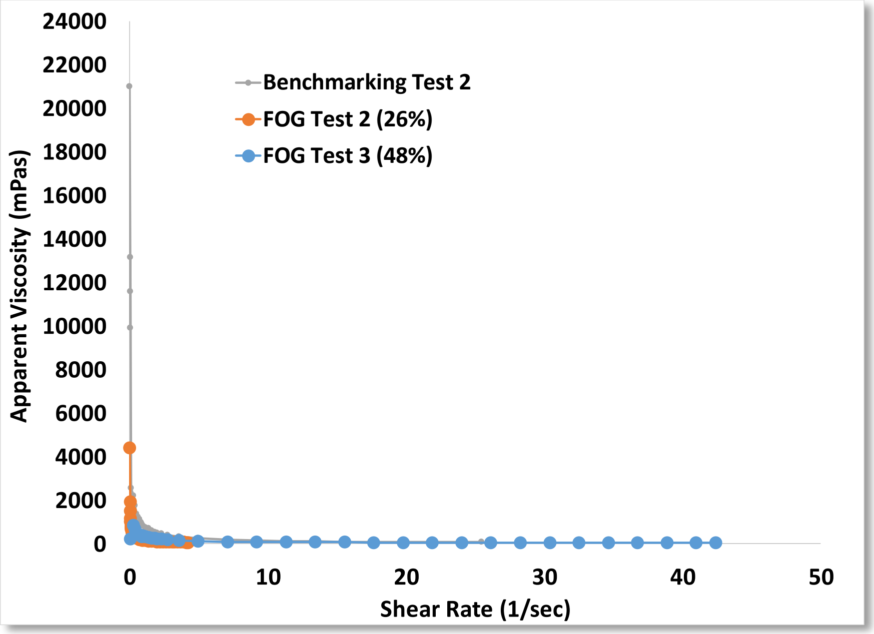
Source: Kennedy/Jenks Consultants

In general, an M/D ratio of less than 10 is considered favorable for dewatering. Benchmarking Test 1 had the lowest and most favorable M/D ratio and exhibited the least polymer demand. M/D ratio increased in the Benchmarking Test 2. In FOG Test 1, the M/D ratio was the lowest of all the FOG tests and exhibited better dewatering when compared to the FOG tests 2 and 3. FOG Test 3 had a lower M/D ratio than FOG Test 2, but the former only exhibited a very small improvement in percent solids after dewatering and polymer demand did not improve. Other studies have found that at M/D ratios between 5 and 40, the cake solids percentage decreased with increasing M/D ratios, as would be expected from the divalent cation bridging theory. At M/D ratios above 40, the cake solids percentage does not change by much, showing that the M/D ratio has less of an effect (Higgins and Rajagopalan 2017). With respect to the FOG codigestion tests, these findings from the current study indicate that other factors apart from M/D ratio may have affected dewatering.

5.2.8 Digester Rheology and Rapid Volume Expansion

Viscosity and yield stress affect digester operations such as mixing, pumping, dewatering, and rapid volume expansion (RVE) due to gas holdup. As the TS concentration increases, the viscosity also increases, as do other important rheological properties such as the yield stress. Figure 41 compares the apparent viscosity profile as a function of shear rate of all the FOG Tests.

Figure 41: Viscosity and Yield Stress

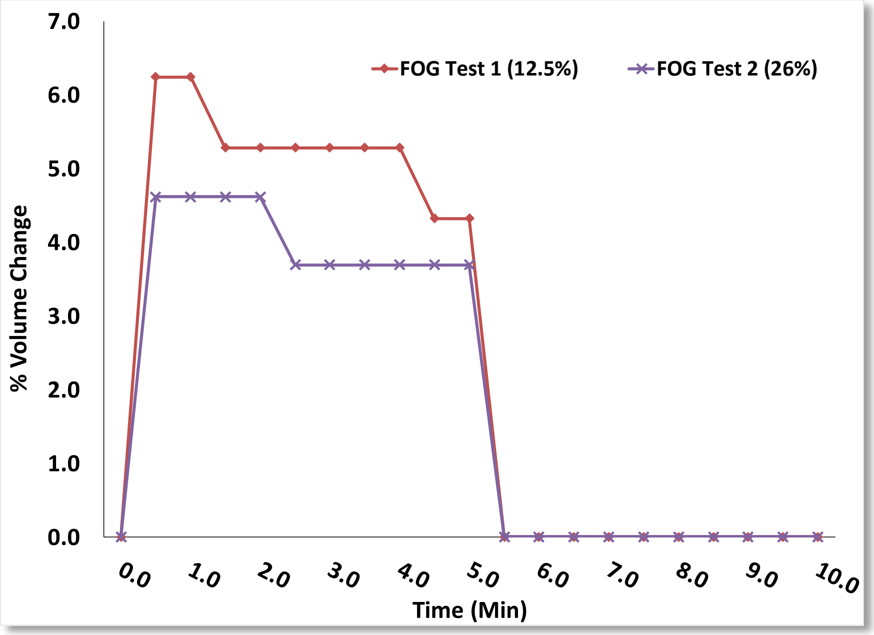


Source: Kennedy/Jenks Consultants

The digested sludge typically behaves as a non-Newtonian fluid with shear thinning behavior (Higgins and Rajagopalan 2017). This is presented in Figure 41 where the shear rate increases, and the viscosity decreases. The apparent viscosities were not significantly different between the three tests at any given shear rate. It was not possible to determine if codigestion with FOG affected the viscosity.

Viscosity, shear stress, and the RVE are all related to each other. RVE is mainly attributed to gas holdup in digester sludge. In the practical aspect of digester operation, the shear rate is a measure of the mixing. Because of the shear thinning and yield behavior of the digested sludge (as seen in Figure 41), gas holdup becomes greater as the shear rate in the digester decreases (or when mixing is stopped). Viscosity then increases and the digester sludge then exhibits yield stress, which correlates to volume expansion. As gas is continuously produced in the digester, it becomes entrapped within the solids, resulting in volume expansion of the digester contents. The RVE was measured (Figure 42) and indicates the change in volume due to foaming and gas holdup.

Figure 42: Rapid Volume Expansion



Source: Kennedy/Jenks Consultants

The changes in the sludge volume during mixing in the various FOG tests were less than 7 percent. The only significant trend observed was the lower volume expansion with increasing FOG loading. This volume change of the FOG tests is like that of Benchmarking Test 1. In Benchmarking Test 2, due to foaming episodes in the digester, the volume change was high. With FOG codigestion, the volume change reverted to low levels similar to Benchmarking Test 1. This suggested that, under such codigestion conditions, with similar FOG characteristics, RVE risk is predicted not to be significant for this digester. Any codigestion with FOG or other co-waste with similar characteristics, is likely not be a direct cause to RVE in the digester.

5.3 Summary of FOG Codigestion Tests

Results during benchmarking and FOG codigestion were evaluated for potential effects on viscosity, foaming or volume expansion, dewatering, solids production, and cake quality in terms of odors. The main findings of this work are the following:

1. Overall, the addition of FOG increased the total gas production, VSR, and unit gas production. The addition of the highest volumes of FOG, produced a 58 percent increase in total gas production when compared to the benchmarking test. Results are summarized in Table 36.

Table 36: Summary of Gas Production, VSR, and Unit Gas Production

Test	Total Gas Production (cu.ft.)	VSR (%)	Unit Gas Production (cu.ft./lb VS reduced)
FOG Test 1 (12.5%)	163,400	64.09	14.47
FOG Test 2 (26%)	220,700	64.27	16.05
FOG Test 3 (48%)	265,900	66.00	19.65

Source: Kennedy/Jenks Consultants

2. Methane content increased steadily with increasing FOG. Methane gas production increased by approximately 7 percent during FOG Test 3 compared to Benchmarking Test 2.
3. H_2S concentration increased by an order of magnitude in FOG Test 2 compared to the other tests due to a reduction in ferric chloride dosing and returned to normal levels during FOG Test 3, and the plant dosing issue was resolved. This indicated that the increase in sulfide levels was independent of the FOG addition.
4. Several different parameters were investigated to evaluate the potential effects on dewatering. Polymer demand increased with increasing FOG feed. Dewatered solids content did not improve with addition of FOG. The reasons for the lower than expected percent solids in the cake in the last two tests could be related to the lack of sufficient acclimation time.
5. Polymer demand increased with increasing M/D ratio. Dewatered solids percent content only decreased marginally with increasing M/D ratio. This trend suggests that apart from M/D ratio, other factors influence dewatering and polymer demand. The addition of FOG affected the M/D ratio. M/D ratio decreased with the highest FOG loading (Table 37).

Table 37: Summary of Dewatering Results

Test	M/D Ratio	Polymer Demand (lbs/DT)	Difference Relative to Bench-marking Test 2 (%)	De-watered Cake Solids (%)	Difference Relative to Bench-marking Test 2 (%)
Benchmarking Test 1	3.5	28	—	17.04	—
Benchmarking Test 2	9	35	—	18.50	—
FOG Test 1 (12.5%)	19.6	28.6	18.3	21.58	-16.7
FOG Test 2 (26%)	41.7	30.75	12	18.12	2.05
FOG Test 3 (48%)	26.6	34.37	1.8	18.61	-0.59

Source: Kennedy/Jenks Consultants

6. Addition of FOG affected cake odor. An increase in odor at lower amount of FOG addition was observed, followed by decrease in odor production at higher organic loading, as with other high strength waste codigestion studies (Rajagopalan et al. 2013).

7. Overall, the effect of codigestion did not exhibit a considerable effect on dewatering. It could have been limited by the steady state acclimation as well as other uncontrolled variables that occurred during full-scale digester operation.
8. The addition of FOG had very little to no effect on digestate viscosity and yield stress.
9. The rapid volume expansion (RVE) potential decreased with increasing FOG addition.

CHAPTER 6: Novel Food Waste Pre-Processing and Codigestion Demonstration

This chapter describes the codigestion of food waste (FW). The FW was processed by the OREX press at the Recology facility and diluted and polished on site at SVCW, prior to being fed to the digester. Results from the FW codigestion tests are compared with the corresponding FOG codigestion tests (12.5 percent FW with 12.5 percent FOG and 25 percent FW with 25 percent FOG tests). Benchmarking Test 1 is used as the control case to compare these results as it has the closest range of sludge VS load as that of the FW tests.

6.1 Testing Approach

The FW preprocessing and codigestion demonstration consisted of the following:

- Extraction of the digestible fraction of commingled FW using the OREX unit installed at the Recology San Francisco facility
- Polishing and dilution of the extracted material from the OREX unit using the polishing unit (paddle finisher) installed at the SVCW site
- Operation of the digesters by adding preprocessed and polished FW under two FW loading conditions (Table 38)
- Analyses of feed sludge, FW and digester sludge samples, biogas measurements, dewatering characteristics, and cake odor

The initial goal of the food waste test involved adding the same load (VS) of sludge as the FOG tests to the digester and adding FW in a manner to maintain the same co-waste VS to sludge VS ratio as in the FOG tests This would allow for a direct comparison of digester performance during FOG and FW codigestion. However, due to some limitations in the amount of FW available from Recology (approximately 4 to 5 tons/day) during the project period, this approach was slightly modified. Accordingly, the sludge load to the digesters was decreased while keeping the FW VS to sludge VS ratio similar to those used in the FOG tests.

The revised target sludge loading was maintained over most of the FW testing period. However, wet weather conditions and routine operational issues with OREX, as well as the polishing unit, resulted in occasional lower than targeted VS loading ratio. Thus, steady-state operation at the target loading ratio could not be completely established and verified during the test. These operational issues were resolved after the first two weeks of OREX operation. These issues were mitigated by some routine maintenance such as oil changes, replacement of hoses due to wear and tear, and a remote reset on the sensors by the equipment vendor. The percentage of sludge and FW added to the digester for each test is outlined in Table 38.

Table 38: Digester Food Waste Loading Conditions

Test	Loading (lbs VS/cu.ft./day)	Food VS: Sludge VS (%)
FW Test 1	~0.047 (~0.04 sludge + <0.01 Food Waste VS)	12.5
FW Test 2	~0.045 (0.04 sludge + ~0.01 Food Waste VS)	25

Source: Kennedy/Jenks Consultants

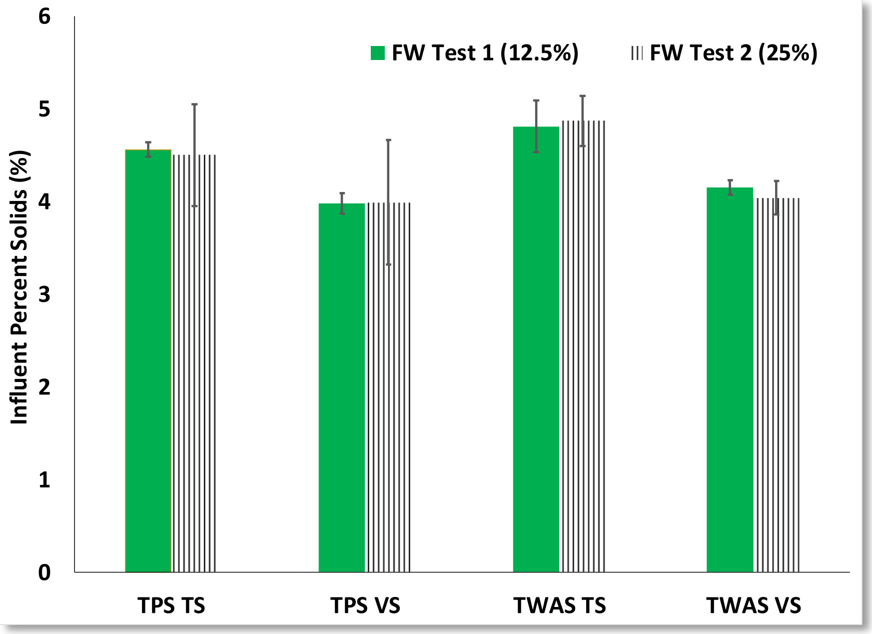
6.2 FW Tests: Results and Discussion

The results of the FW characterization, bench-top respirometry, gas production, polymer demand, cake odor tests, and full-scale digester performance results are presented and discussed in this section.

6.2.1 Influent Sludge Solids Content

Figure 43 shows the TS and VS concentrations of the thickened primary sludge (TPS) and thickened waste-activated sludge (TWAS) during the FW studies.

Figure 43: Average Daily Feed Sludge TS and VS for Each Test



Note: Error bars represent standard deviation.

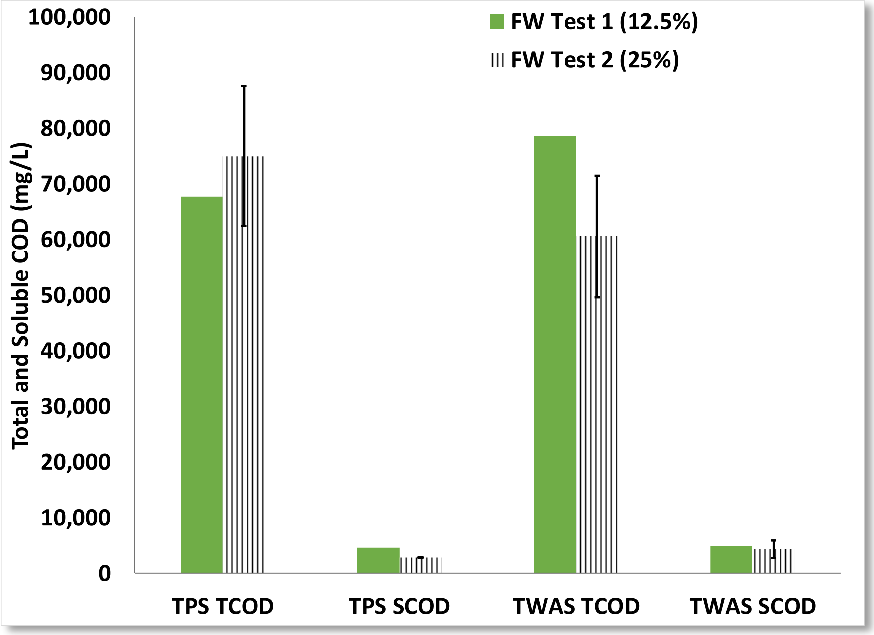
Source: Kennedy/Jenks Consultants

The average TPS TS and VS concentrations for both the FW tests were almost equal. The TS content of the TPS during FW tests 1 and 2 were about 4.5 percent and 3.9 percent for VS content. The TWAS TS and VS were also similar between the two tests (approximately 4.8 percent for TS and 4.2 percent for VS). This indicated that the average influent sludge quality was similar in the two tests. In general, the TPS and TWAS solids content measured during the FW tests were similar to those measured during the benchmarking and FOG tests. As observed during these earlier tests, the variation (standard deviation) in the solids content between samples was likely due to normal day-to-day fluctuations in influent wastewater characteristics.

6.2.2 Influent Sludge Solids COD

The total COD (TCOD) and soluble COD (sCOD) of the influent TPS and TWAS was measured for FW tests 1 and 2. The results from the COD analyses are shown in Figure 44.

Figure 44: Average Daily Influent Sludge Total and Soluble COD



Note: Error bars represent standard deviation.

Source: Kennedy/Jenks Consultants

The TPS and TWAS TCOD concentrations ranged from approximately 67,000 mg/L to 75,000 mg/L and 60,000 to 78,000 mg/L, respectively. The variations in TCOD concentration are similar to those observed in the benchmarking and FOG tests. In FW Test 1, the sCOD concentration in the TPS and TWAS was lower than the TCOD just as was observed during the prior benchmarking and FOG tests. The TWAS sCOD over both tests varied only about 12 percent.

6.2.3 FW Sample Characterization and Respirometry Analysis

This section provides and discusses the results of the FW characterization analyses. For every FW delivery, the polished and diluted FW was sampled and analyzed. The offloaded FW was diluted to about 7 to 8 percent solids in the receiving tank, which was the maximum TS that could be pumped by the paddle finisher feed pump. The FW was further diluted in the paddle finisher, resulting in a final FW TS percentage of 3 to 6 percent fed to the digester.

6.2.3.1 OREX and Polished FW Quantity and Quality

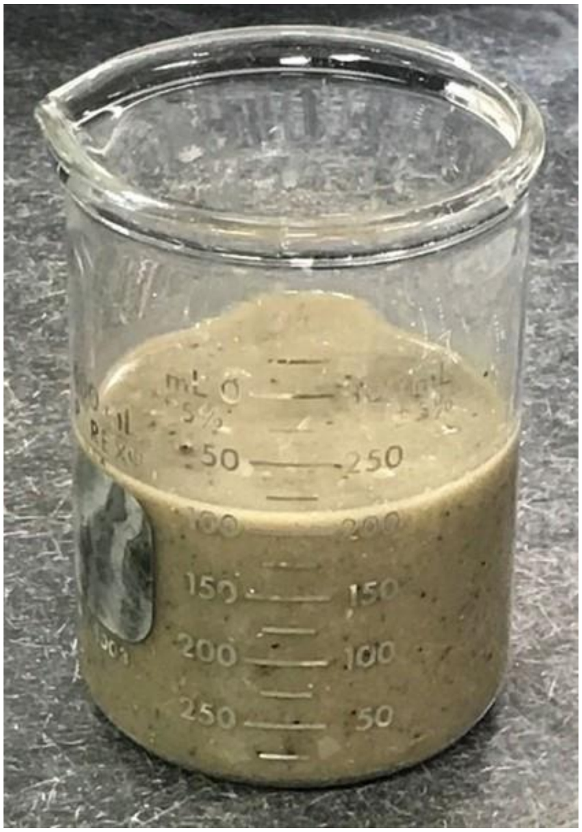
Pictures of the truck-hauled FW (produced by OREX) and that of the polished and diluted FW (produced by the paddle finisher) are shown in Figure 45 and Figure 46, respectively.

Figure 45: Picture of FW Sample From Truck

Source: Kennedy/Jenks Consultants

Figure 45 shows the FW sample from the truck. The source is a commingled MSW stream, which is attributed to the presence of non-organic material, debris, fibrous material, plastics, rags, and other material.

Figure 46: Picture of Polished and Diluted FW Fed to Digester



Source: Kennedy/Jenks Consultants

Dilution and polishing operations removed most of the debris and produced a more homogenous product at a TS content of approximately 4 to 6 percent.

The FW tonnage, TS percentage, VS percentage, TCOD, and sCOD were measured to monitor the quality of the delivered OREX waste. A total of eight samples were collected and analyzed during the operational period. A summary of FW quality and quantity data for FW tests 1 and 2 is provided in Table 39. Polished and diluted FW samples were collected for each load to determine the FW characteristics after dilution and polishing. The FW volume, TS percentage, VS percentage, and TCOD were measured with each load during the test period to monitor the FW quality and to determine the digester loading rates. A summary of these analyses over the two tests is shown in Table 39.

Table 39: Characteristics of Truck Hauled in FW and Diluted and Polished FW

Parameter	FW Test 1 Hauled in FW	FW Test 1 Diluted and Polished FW	FW Test 2 Hauled in FW	FW Test 2 Diluted and Polished FW
Quantity of FW received (TPD)	2.8 ± 0.9	—	3.8 ± 0.3	—
Polished and diluted FW fed to digester (GPD)	—	11,470 ± 4120	—	5,207 ± 43
TS (%)	N/A	1.9 ± 0.6	27 ± 6.4	6.2 ± 0.2
VS/TS Ratio	N/A	0.86 ± 0.03	0.83 ± 0.08	0.88 ± 0.04
TCOD (mg/L)	N/A	65,800 ± 5560	325,750 ± 38,537	59,500 ± 13530
sCOD (mg/L)	N/A	19,730 ± 510	69,000 ± 1781	13,360 ± 6700

Source: Kennedy/Jenks Consultants

From Table 39, the average tonnage and solids content of the FW received during Test 2 was higher than that of Test 1. However, the tonnage of the OREX waste received varied from day to day mainly due to differences in the feed going into the OREX press. Some equipment startup issues also contributed to the low output from OREX, which was fixed prior to the time of Test 2. The volume of polished and diluted FW fed to the digester during the first test was 54 percent higher than the second test. Although higher volume of FW was fed to the digester during Test 1, the TS concentration of the FW fed to the digester was much higher during FW Test 2 (6.2 percent compared to 1.9 percent). The increase in the TS concentration was primarily due to a new screen being installed in the paddle finisher as well as optimization of the FW receiving and polishing operations. The new screen was more effective at removing the fibrous material and rags contained in the FW through the paddle finisher and preventing the screen from clogging at a lower water dilution. The TCOD concentration of the truck FW sample was determined as 325,750 mg/L (diluted about five times prior to feeding the digester). The TCOD concentration of the polished and diluted FW ranged from 59,500 to 65,800 mg/L, which was in the range of the TCOD concentration measured in TPS and TWAS over the various benchmarking, FOG, FW tests, suggesting that the TCOD was in the range of sludge TCOD. The average sCOD concentration of the FW was much higher than measured for the TPS and TWAS (about three times more), indicating that potentially more soluble organic matter is available in the FW than sludge for biogas production.

6.2.3.2 Other Feed Sludge and FW Characteristics

In addition to TCOD, TS percentage, and VS percentage, other constituents in the digester feed can affect digester performance. The PS, TWAS, and FW were analyzed for several characteristics such as CHN (carbon, hydrogen and nitrogen), electrical conductivity, and ammonia during the FW tests. The results are summarized in Table 40.

Table 40: Representative Characteristics of Feed Sludge and FW

Parameter	TPS	TWAS	FW
Carbon : Hydrogen : Nitrogen (CHN)[1]	44 : 6.3 : 2.6	43 : 6.2 : 7.8	42 : 6.2 : 2.5
pH	6.2 ± 0.1	7.0 ± 0.4	4.2 ± 0.13
Electrical Conductivity (mS/cm)	1.1± 0.1	2.7 ± 0.3	5.8 ± 0.7
Ammonia-N,(mg/L NH_4-N)	73 ± 24	150 ± 27	90 ± 33

[1] **All values are average from both the FW tests.**

Source: Kennedy/Jenks Consultants

The CHN content of the TPS and TWAS did not vary significantly from that of the benchmarking and FOG tests and was consistent with results of other codigestion studies, where reported values range from 44 to 49 percent C, 6 to 8 percent H and 2 to 4 percent N for PS and 39 to 42 percent C, 6 to 7 percent H and 7 to 8 percent N for TWAS (Higgins and Rajagopalan 2017). Similarly, the FW CHN content was in the range of other pre-processed FW (33 to 47 percent C, 3 to 7.6 percent H and 1 to 4 percent N) reported in the literature. FW typically has been reported to have a higher nitrogen content than FOG because it has significant protein content as compared to other wastes (Long, Aziz, et al. 2012). However, such higher nitrogen values are not observed here and the nitrogen content is similar to that of FOG reported in Chapter 5. This is potentially because the source of the FW was a commingled waste stream rather than the source-separated waste stream that has been commonly used in the other studies mentioned here.

The pH of the feed sludge was in a normal range and was similar to that measured during benchmarking and FOG tests (6.0–7.3). The pH of the FW (approximately 4) was more acidic than the feed sludge and was in similar ranges from other studies in literature (Higgins and Rajagopalan 2017; Long, Aziz, et al. 2012).

Electrical conductivity of the feed sludges did not vary significantly over time and were similar to the values exhibited during the prior tests. The conductivity of FW samples were higher than that of both sludge and FOG indicating potential presence of high content of salts or ions in the FW (Ma et al. 2011). Individual cation concentrations were also measured and M/D ratio was calculated. M/D ratio decreased greatly in comparison to the FOG tests due to elevated levels of calcium (Section 6.3.4.4).

Ammonia concentration in the feed sludges during the FW tests was significantly less than that of the FOG tests. This was potentially caused by wet weather rain events. Ammonia concentration in FW was 23 percent more than that of TPS and 40 percent less than TWAS. Hence, FW ammonia levels are not significantly higher than sludge, the reason for which is the source of the FW. The FW in this study is from commingled MSW stream. Typically, source-separated FW contains high ammonia due to presence of proteinaceous compounds. Such lower N concentration in this FW could balance out the higher N concentration in some feed sludges and reduce the potential for ammonia toxicity.

6.2.3.3 Respirometry Gas Production Estimates

Bench-scale respirometry tests were conducted to determine the digestible fraction of the COD in the diluted and polished FW. In addition to determining the digestible fraction of the FW, the respirometry test was used as an indicator for inhibitory compounds in the FW that may negatively affect the digestion process. This estimate was particularly important for this study because the source of the FW was commingled MSW rather than the source-separated MSW used in most other studies. The control sludges used were from SVCW sludge samples. The gas production obtained during the respirometry test was also used to validate the full-scale digester gas production, which may have had inconsistencies due to issues with the gas flow meters. The results of the FW respirometry tests are provided in Table 41.

Table 41: Gas Production From Respirometry of OREX Food Waste

Sample	Diluted and Polished FW
Mass of FW added (g)	10
Total COD (mg/L)	65,800 ± 5560
Total gas production (mL)	770
Total gas production (mL/g FW)	77
Difference of total gas production and control (mL)	296
Calculated gas production (cu.ft./ton of FW added)	1,046
Methane content (%)	64
Methane yield (mL/g VS fed)	455

Source: Kennedy/Jenks Consultants

The biochemical methane production from the polished and diluted FW was approximately 455 mL/g VS. In comparison, the source-separated FW collected from post-consumer facilities at the City of San Francisco and ground by a hammer mill, had methane yields of 348 and 435 mL/g VS applied, respectively, after 10 and 28 days of digestion at 50°C (122°F) in lab-scale. The average methane content of biogas was 73 percent and the average VS destruction was 81 percent after 28 days of digestion (California Energy Commission, 2005; Zhang et al., 2007). The pre-processed FW used in this study exhibited similar methane yield but a much lower methane content (64 percent) during the respirometry test (Table 42). Other values presented in the literature include 344 to 364 mL/g VS MSW (Zhang, Banks, et al. 2012), 401 mL/g VS MSW (Zhang, Banks, et al. 2012) for FW only digestion of either SS-FW or OFMSW, 158 to 553 mL/g VS MSW depending on different sources and pretreatment methods (Hansen et al., 1998; Zhang et al., 2011)). Post-consumer source-sorted FW gas production from cafeterias in China was 560 mL/g VS (Mu et al., 2018). The respirometry data from the pre-processed FW used in this study exhibits similar methane potentials of various other comparable wastes with different preprocessing methods listed in the previously mentioned literature sources.

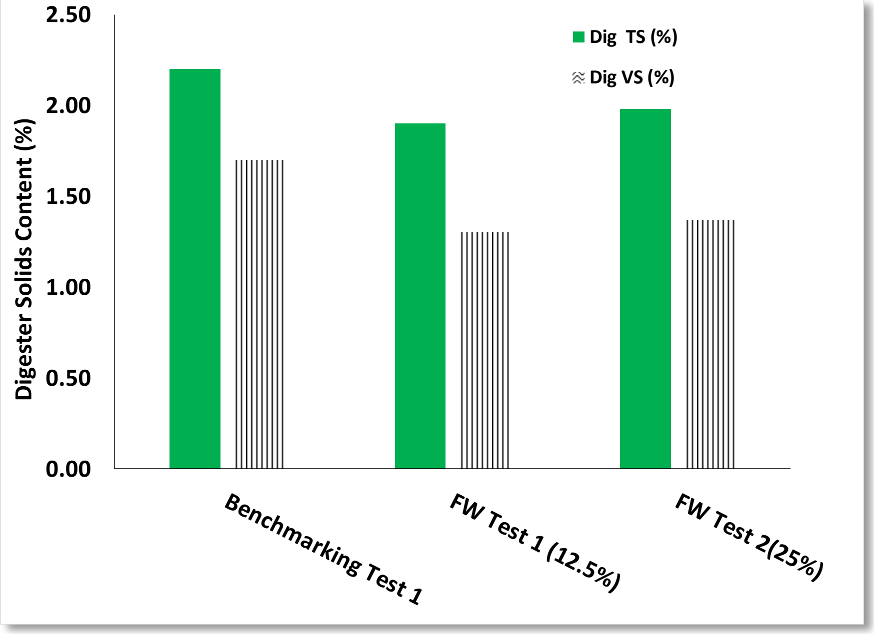
6.2.4 Digester Performance: Solids Content

The digester effluent TS and VS concentrations were measured for the two FW tests and compared to those obtained during the FOG tests. The TS and VS concentrations in the influent TPS, TWAS, and received FW were also measured.

6.2.4.1 Digester Solids

The digester effluent TS and VS concentrations were measured during the FW tests and compared to those obtained during the FOG tests. The results from these analyses are summarized in Figure 47.

Figure 47: Average Daily TS and VS in the Digester



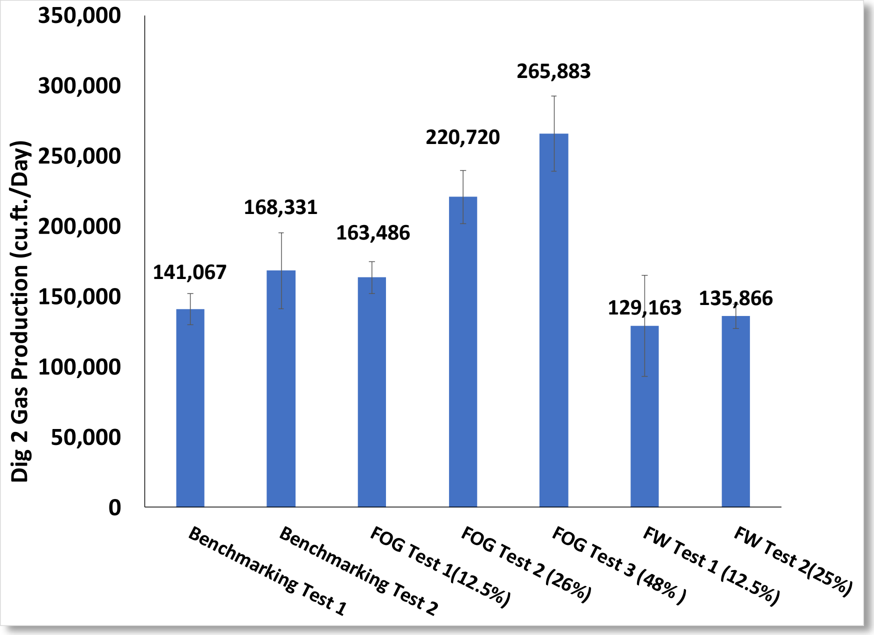
Source: Kennedy/Jenks Consultants

The average TS and VS content in the digester during FW tests 1 and 2 was 1.90 percent and 1.30 percent and 1.98 percent and 1.37 percent, respectively. The TS and VS during FW Test 2, conducted at higher TS and VS loading, was approximately 4.2 percent and 5.3 percent higher compared to the TS and VS in the digester during FW Test 1. The extra mass of influent solids coming into the digester for Test 2 was only 5 percent more than that of Test 1. In comparison to Benchmarking Test 1, the influent VS in the FW tests was 24 percent and 20 percent less than this test. Correspondingly, the decrease in the digester VS over these two FW tests was 24 percent and 19 percent respectively, compared to the same benchmarking test. When compared to Benchmarking Test 1, addition of FW did not increase the amount of solids in the digester during the FW tests. It is difficult to show from this data if the FW is more digestible than the sludge solids. To determine this, gas production, VSR, and unit gas production were estimated as discussed in the following section.

6.2.4.2 Total Gas Production, VSR, and Unit Gas Production

Figure 48 shows the average daily gas production for all the tests. The feed sludge volumes and VS loading details are shown in Table 42.

Figure 48:Total Gas Production for All Tests



Note: Error bars represent standard deviation.

Source: Kennedy/Jenks Consultants

Table 42: Volumes of Sludge and FOG Fed and Total Gas Production

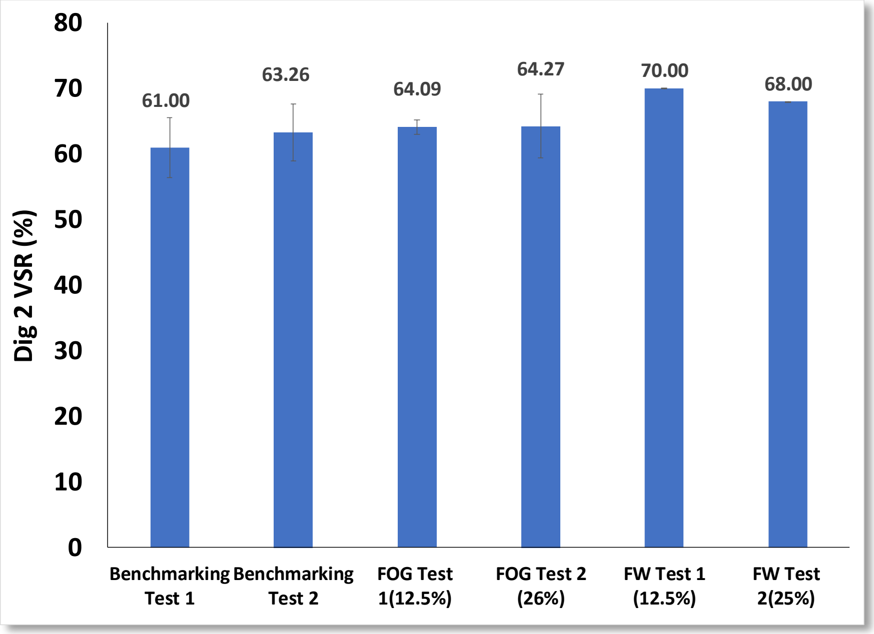
Test	VS Loading to Digester (lbs VS/ cu.ft./d)	Volumes of Feed (GPD)	Influent Sludge and FOG/FW VS (lb/d)	Influent FOG/FW Volume: Sludge Volume	Influent FOG/FW VS (lb/d)	Total Gas Production (cu.ft/d)
Bench-marking Test 1	0.07 lbs VS/ cu.ft.	S: ~40,400	14,838	—	—	141,067
Bench-marking Test 2	0.11 lbs VS/cu.ft.	S:~ 70,000	22,535	—	—	168,331
FOG Test 1 (12.5% FOG)	S: 0.073 F: ~0.01	S: 45,600 F: 8,250	17,485	0.18	1943	163,486
FOG Test 2 (26% FOG)	S: ~0.08 F:~0.02	S: 57,000 F: ~12,800	20,255	0.22	4180	217,283
FOG Test 3 (48% FOG)	S: ~0.066 F:~0.032	S: 41,500 F: ~28,000	20,936	0.67	~6000	265,883
FW Test 1 (12.5% FW)	S: ~0.04 FW: <0.01	S: 29,894 FW: 11,469	11,333	0.38	1245	129,163
FW Test 2 (25% FW)	S: ~0.04 FW: ~0.01	S: 29,555 FW: 5207	11,911	0.18	2350	135,866

S: Sludge, F: FOG, FW: Food Waste

Source: Kennedy/Jenks Consultants

The total VS load to the digester during FW Test 1 (11,333 lbs/d) and FW Test 2 (11,911 lbs/d) was almost the same, and the gas production in the FW Test 2 was higher than that in FW Test 1 by 5 percent (129,163 cu. ft/d VS 135,866 cu.ft./d). The increase in gas production can be attributed to the higher FW loading in FW Test 2 (2,350 lbs/d) compared to FW Test 1 (1,245 lbs/d), achieved by better operations of the polishing unit. When compared to Benchmarking Test 1, which received 27 percent higher sludge flow and no FW, the FW test produced only 3.7 percent less gas production, suggesting the contribution of FW loading to gas production. Figure 49 shows the average VSR for the FW tests. VSRs for the benchmarking and FOG tests are also provided for comparison.

Figure 49: VSR for FW and Benchmarking Tests



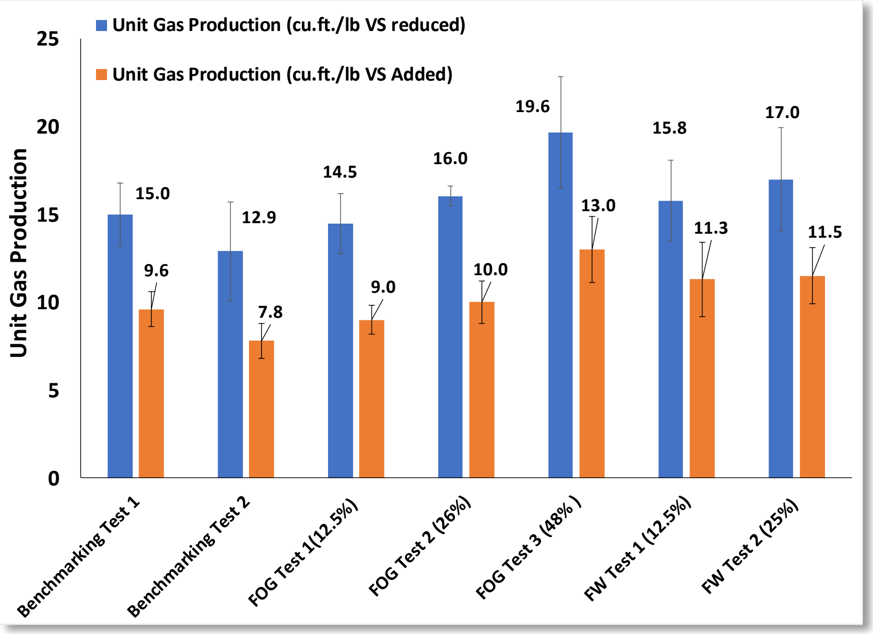
Note: Error bars represent standard deviation.

Source: Kennedy/Jenks Consultants

The average VS loading for Benchmarking Test 1 was approximately 42 percent and 37 percent higher than that for FW Test 1 and Test 2, respectively. Compared to the benchmarking tests that had VSRs of 61 percent and 63.26 percent, the FW tests had much higher VSRs (70 percent and 68 percent, respectively). The increase in VSR observed in the FW tests (15 percent for FW Test 1 and 11.5 percent for FW Test 2) compared to Benchmark Test 1, indicated that FW addition had a positive effect on digester performance.

The improvement in VS with additional FW loading can be explained by the increasing ratio of VS from FW in the digester feed, as well as the synergistic effect of codigestion (Higgins and Rajagopalan 2017). A previous literature review study reported VSR between 51 to 70% for codigestion of various sources of FW and OFMSW with sludge, at different feed ratio conditions (Chow et al., 2020). The VSR from the current study is within the range reported in literature during food waste codigestion. The improvement in digester performance with increasing FW addition can also be seen from the unit gas production as illustrated in Figure 50.

Figure 50: Unit Gas Production



Note: Error bars represent standard deviation.

Source: Kennedy/Jenks Consultants

Overall, the unit gas production per lb VS destroyed at FW Tests 1 and 2 were 6 percent and 13 percent higher than that observed with Benchmarking Test 1. The unit gas production at lower FW loadings was comparable to unit gas production at comparable FOG VS loading. When normalized to digester VS load added, FW Test 1 and FW Test 2 exhibited much higher gas production than Benchmarking Test 1. The gas production per pound of VS load was approximately 9.5 cu. ft/lb-VS and 7.8 cu. ft/lb-VS for Benchmarking Test 1 and 2, respectively and approximately 11.4 cu. ft/lb-VS for both FW tests. These data suggested that per unit VS added the FW has more potential to produce gas than when sludge alone is digested.

These results are also supported by previously published FW studies by others. Comparable literature values for source-separated FW that was ground and polished by a paddle finisher had a peak value of 8.5 cu.ft. CH_4/ lb FW TS when only this FW was digested (Gray et al., 2008). The unit gas production from the FW Test 2, when determined by TS, is about 8 cu.ft. CH_4/ lb FW TS.

6.2.5 Gas Quality

This section discusses the quality of the raw biogas generated in the digester during the FW codigestion.

6.2.5.1 Methane and CO_2 Content

The two primary constituents of biogas are methane and CO_2. The concentration of these gasses can vary depending on the feed stock. The methane and CO_2 content of the digester gas generated during the FW tests was measured to determine the effect of FW on the gas quality. The results from FW Test 1 and FW Test 2 gas analyses and results from the FOG tests, provided for comparison, are summarized in Table 43.

Table 43: Methane Content and Methane Production in FOG and FW Tests

Test	Biogas Production (cu.ft./day)	Methane Content (%)	Average Methane Production (cu.ft./day)	CO_2 Content (%)
Benchmarking Test 1	141,067	59.5	83,934	35.2
Benchmarking Test 2	168,331	62.8	105,712	36.5
FOG Test 1 (12.5%)	163,057	60.2	98,160	38.9
FOG Test 2 (26%)	220,719	60.5	133,535	37.3
FOG Test 3 (48%)	265,883	66.9	177,875	32.9
FW Test 1 (12.5%)	151,533	59.5	90,162	40.3
FW Test 2 (25%)	184,955	59.8	110,603	39.9

Source: Kennedy/Jenks Consultants

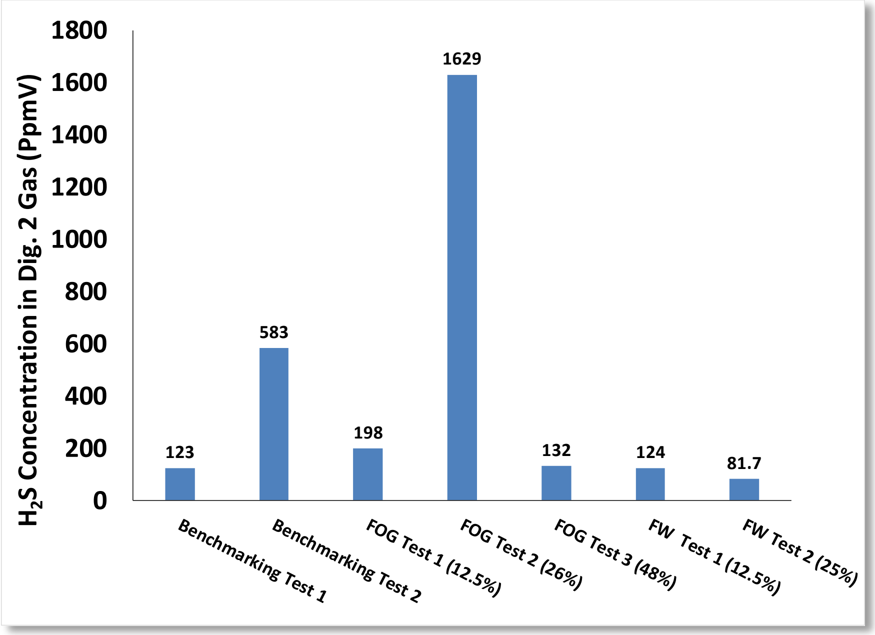
The methane content of the gas generated during FW Test 1 and Test 2 was similar and the CO_2 content differed marginally (about 1 percent) between the two tests. When compared to Benchmarking Test 1, the methane content was similar to FW Test 1 and only marginally different in FW Test 2. At similar co-waste (FOG or food waste) to sludge VS loading ratios, the methane and CO_2 content in the biogas quality from FW tests were similar to that from FOG tests (FOG Tests 1 and 2, and FW Tests 1 and 2). FOG Test 3 had higher methane content and a lower CO_2 content than all the other tests. While the factors influencing this data from FOG Test 3 are not known, FOG codigestion has shown to increase methane content in other studies (Long et al. 2012).

The methane content of the gas from FW Test 1 (shown in Table 43) was lower than the methane content (64 percent) yielded in the bench-top respirometry tests (listed in Table 41). It is not uncommon for the codigestion results generated from bench-scale, pilot- and full-scale FW tests to differ. Studies conducted on pilot- and full-scale digestion of FW have shown the digester gas to have a lower methane content (50 percent to 62 percent) in the range observed in the current study (Long et al., 2012; Trzcinski and Stuckey, 2018).

6.2.5.2 H_2S Production in the Digester

Sulfate and organic sulfate are reduced to H_2S by sulfate-reducing bacteria during anaerobic digestion. The amount of H_2S formed during digestion is dependent on the chemical characteristics of the co-waste fed to the digester, the digester chemistry, and concentration of coagulant (for example, ferric chloride) added. The digester gas was measured for H_2S during the FW tests to determine the effect of FW addition on digester gas H_2S concentrations. The H_2S concentration measured during codigestion of FOG and FW tests is shown in Figure 51.

Figure 51: H_2S Concentrations Measured During the Tests



Source: Kennedy/Jenks Consultants

As illustrated in Figure 51, the digester gas H_2S concentration decreased from 124 ppmV in FW Test 1 to 82 ppmV in FW Test 2, a reduction of approximately 34 percent. This trend in a reduction in H_2S concentration with an increase in co-waste loading was observed between FOG Test 1 and FOG Test 3 also (ferric chloride dosing issues occurred during FOG Test 2). However, it is not known currently if the increase in co-waste was directly responsible for the measured decrease in H_2S levels in the biogas.

Comparable H_2S concentrations were observed in a study performing codigestion of mixed, ground-up, pre-consumer commercial FW slurry where 9 percent FW VS was fed to the digester; however, it is unknown if ferric chloride was added in that facility (Kuo and Dow 2017).

6.2.6 pH, Alkalinity and VFA in Digester

The performance of the digester during FW codigestion was also monitored with digester chemistry indicators such as pH, alkalinity, and volatile acid (VA). It is important that these parameters are in the appropriate range to ensure proper and stable digester operation during FW codigestion. Table 44 compares the pH, alkalinity and VA values measured during Benchmarking Test 1 and the equivalent VS FOG tests (12.5 percent and 25 percent VS).

Table 44: Digester pH, Alkalinity, and VA

Test	pH	Alkalinity (mg/L)	VA (mg/L)	VA/A Ratio
Benchmarking Test 1	7.5 ± 0.02	4600	N/A	0.07
FOG Test 1	7.5 ± 0.02	3900	240	0.06
FOG Test 2	7.5 ± 0.4	4015	190	0.05
FW Test 1	7.5 ± 0.02	4300	160	0.04
FW Test 2	7.6 ± 0.03	4525	245	0.05

Notes: All VA and alkalinity analyses conducted by SVCW laboratory.

Source: Kennedy/Jenks Consultants

The pH was within acceptable operations range in all the tests. Even though the pH of FW itself is acidic (approximately 4.3), the digester remained at a pH of 7.5 or greater. The digester pH did not drop significantly at the FW loadings, indicating the digester was well buffered during the tests. When compared to the benchmarking tests, addition of FW did not have an overall effect on the digester pH. Typically, the protein in FW will tend to increase both the pH and alkalinity, in contrast to FOG addition. The changes in pH are mainly a result of ammonia release from FW due to degradation of nitrogen in the FW protein. The released ammonia reacts to form ammonium and also produces bicarbonate alkalinity (Higgins and Rajagopalan 2017). The high nitrogen content of the protein results in an increase in the digester pH. In this case, the FW did not have significant nitrogen content when compared to source-separated FW sources popularly reported in literature. The nitrogen content was similar to that of FOG, discussed in Chapter 5. As a result, alkalinity only increased 10 percent and 12 percent in FW tests 1 and 2 compared to FOG tests 1 and 2. Published studies using source-separated FW report alkalinity values of approximately 12,000 mg/L for a 20 percent VS FW loading (Higgins and Rajagopalan 2017).

In general, VA decreased with an increase in FW loading, and the VA/A ratios exhibited an increase during FW tests 1 and 2. The VA/A ratios were all less than 0.10, which is often considered a threshold level for stable operation (Wan et al. 2011).

6.2.7 Dewatering and Odor Tests

Using the same dewatering bench-scale method and the polymer for the benchmarking and FOG tests, dewatering of the digested sludge with FW addition was performed at Bucknell University. The following parameters were determined during the dewatering experiments:

- Optimum polymer dose (OPD)
- Percent TS in the dewatered cake
- Digester sludge TS and percent TS of the dewatered cake: an estimate of the net mass of cake generated (that is, mass of sludge requiring disposal)
- Odor production from dewatered cake: Total volatile organic sulfur compounds (TVOSC) such as methyl mercaptan (MT) and dimethyl sulfide (DMS)

6.2.7.1 Optimum Polymer Dose

To determine the effect of FW addition on dewatering, the capillary suction time (CST) curves were developed. The comparison of the OPD for the two FW tests is shown in Table 45.

Table 45: Comparison of OPD for Benchmarking, FOG, and FW Tests

Test	OPD (lbs/DT)
Benchmarking Test 1	28
Benchmarking Test 2	35
FOG Test 1 (12.5%)	28.6
FW Test 1 (12.5%)	32.5
FOG Test 2 (26%)	30.75
FW Test 2 (25%)	32.05

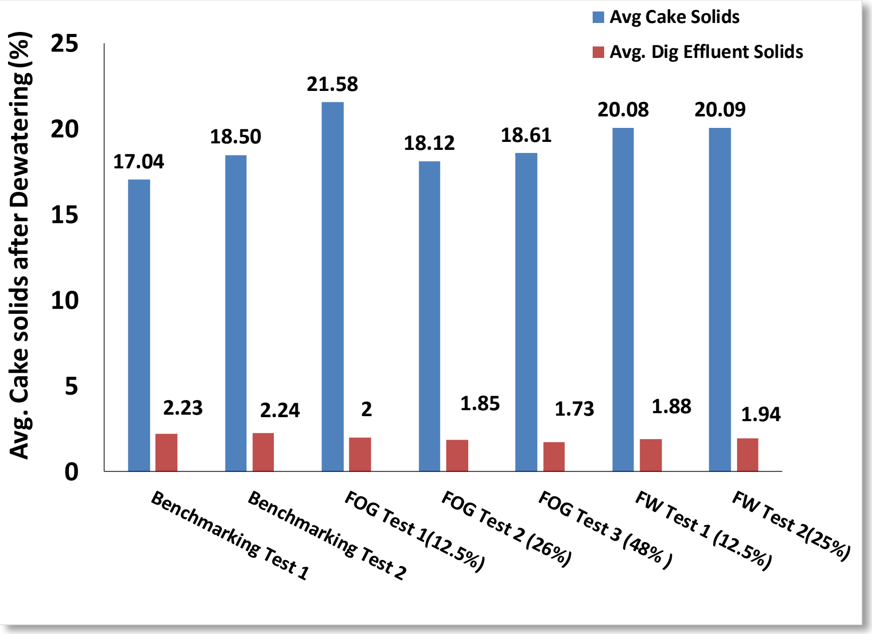
Source: Kennedy/Jenks Consultants

The OPD for both FW tests was similar with a small decrease in the OPD observed for the higher FW loading test. When compared to Benchmarking Test 1, the OPD increased by approximately 16 percent during the FW tests. FOG Test 1 and FW Test 1 had comparable co-waste VS loading. However, the OPD for the FW Test 1 was approximately 14 percent higher than that for the FOG Test 1. Similarly, FOG Test 2 and FW Test 2 had comparable co-waste VS loading, and the OPD was only 4 percent more in FW Test 2 compared to FOG Test 2. These results are consistent with the results from other FW studies reported in the literature. Higgins and Rajagopalan (2017), demonstrated that the OPD in control and FW codigestion tests were similar at lower digester loading rates, and the OPD increased to levels greater than the control, with the exception of one test conducted with pre-consumer FW addition.

6.2.7.2 Dewatered Solids

Improving the solids content of dewatered cake solids anaerobically digested sludge can provide a substantial benefit to the WWTP by decreasing the amount of sludge that has to be hauled off site for disposal. Digested sludge from each of the tests were sent to Bucknell University to determine their dewaterability. The percent solids of the dewatered cake for the benchmarking, FOG, and FW tests is shown in Figure 52.

Figure 52: Average Cake Solids After Dewatering



Source: Kennedy/Jenks Consultants

The percent total solids in the dewatered cake from the Benchmarking Test 1 was 17 percent. In FW Test 1 and Test 2, the dewatering percent solids improved to about 20 percent, an 18 percent increase compared to Benchmarking Test 1. In comparison with the codigestion of FOG in the prior tests, the dewatered cake solids exhibited a 7 percent decrease in FW Test 1 compared to FOG Test 1 and an 11 percent increase in FW Test 2 compared to FOG Test 2.

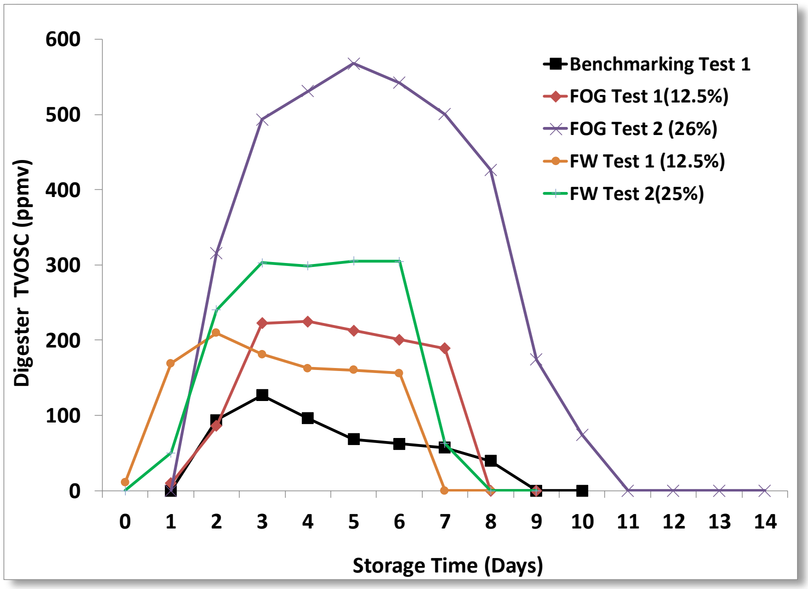
Based on past research on full-scale codigestion studies, FW addition was reported to improve dewatering. Correlations were developed for dewatered solids data from codigestion studies, where the normalized percent change in wet solids leaving the plant was plotted against the percent change in the VS loading to the digester due to the different co-wastes. A majority of these co-wastes were pre- and post-consumer FW. The predicted decrease in the wet cake leaving the plant for a 12.5 percent VS from FW addition was about 6 percent and that from 25 percent FW test was about 0 percent (no net change) (Higgins and Rajagopalan 2017). These literature values compare with an observed decrease of about 18 percent from both FW tests demonstrated by the results in this section. This indicated that addition of FW improved the dewatered cake solids after codigestion.

Overall, FW addition improved dewatered cake solids content when compared to FOG codigestion. FOG tests 2 and 3 as well as FW tests 1 and 2 were performed with minimal time (three to four days) for acclimation. There may also have been higher ferric chloride dosing to the digester during FW Test 2, which could have improved dewaterability of the sludge. These two factors potentially affect dewatering during the FW tests.

6.2.7.3 Cake Odors Production

Compounds associated with the generation of dewatered cake odor are the total volatile organic sulfur compounds (TVOSCs) such as MT and DMS (Higgins et al. 2008). Figure 53 summarizes the TVOSC values measured for the dewatered cake during FW testing, where the odor measurements for the two corresponding FOG tests as well as Benchmarking Test 1 are also provided for comparison.

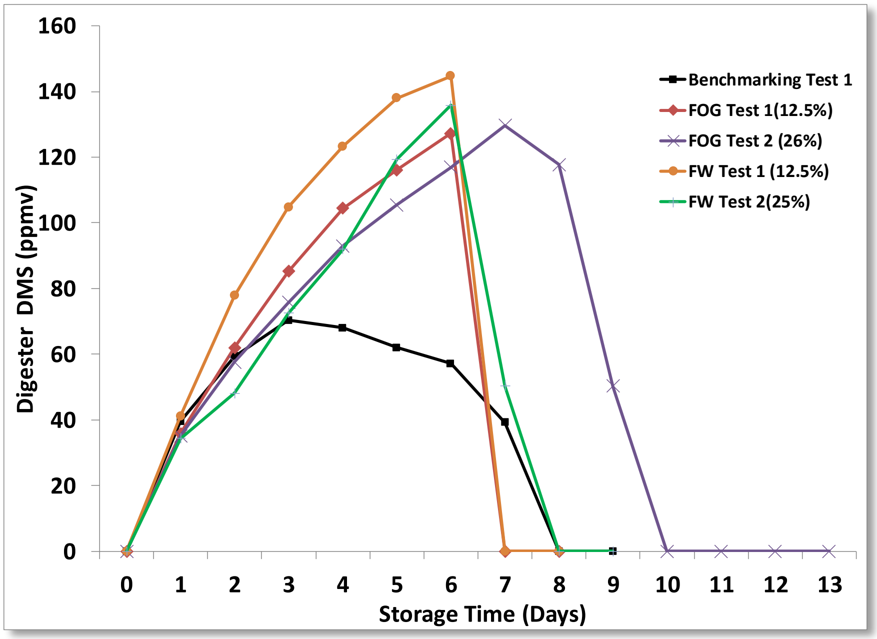
Figure 53: Peak Odor Production (TVOSC) During Dewatered Cake Storage



Source: Kennedy/Jenks Consultants

TVOSC concentrations for FW tests 1 and 2 were lower than those observed for the FOG tests with comparable VS loading (FOG tests 1 and 2, respectively). But the FW test TVOSC was higher than that for Benchmark Test 1. FW Test 2 concentrations were 46 percent higher than FW Test 1. FW Test 1 peak values were 7 percent lower than FOG Test 1. FW Test 2 values were 46 percent lower than those of FOG Test 2. It is interesting to note that the peak value for FW Test 1 was attained at day three; whereas, FW Test 2 peaked on day six. The odor production decreased to below detection levels on days eight and nine respectively in the two tests. Figure 54 shows concentration levels of the individual odor-causing compound, DMS.

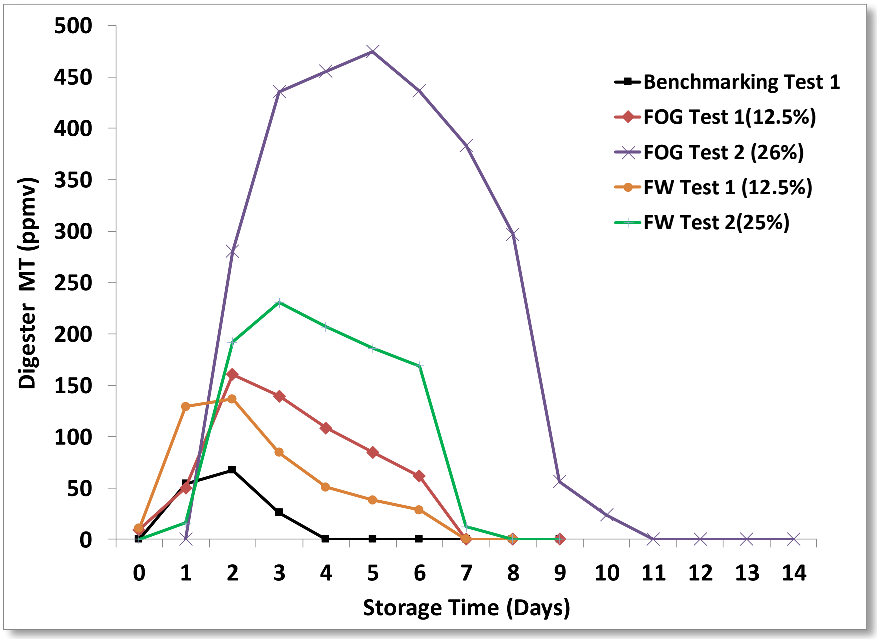
Figure 54: Peak Odor Causing Compounds During Dewatered Cake Storage (DMS)



Source: Kennedy/Jenks Consultants

Unlike TVOSC trends, the peak DMS (a constituent of TVOSC) levels did not vary significantly at different FW loadings. DMS exhibited a 7 percent increase in FW Test 2 compared to FW Test 1. FOG test 1 and 2 concentrations were very similar (approximately 2 percent variation). The duration of the DMS emissions were the same for FOG Test 1 and FW Test 1. The DMS concentrations fell to below detection limits on day 8 for FW Test 1 and day 10 for FW Test 2. Figure 55 shows concentration levels of the individual odor-causing compound, MT.

Figure 55: Peak Odor During Dewatered Cake Storage (MT)



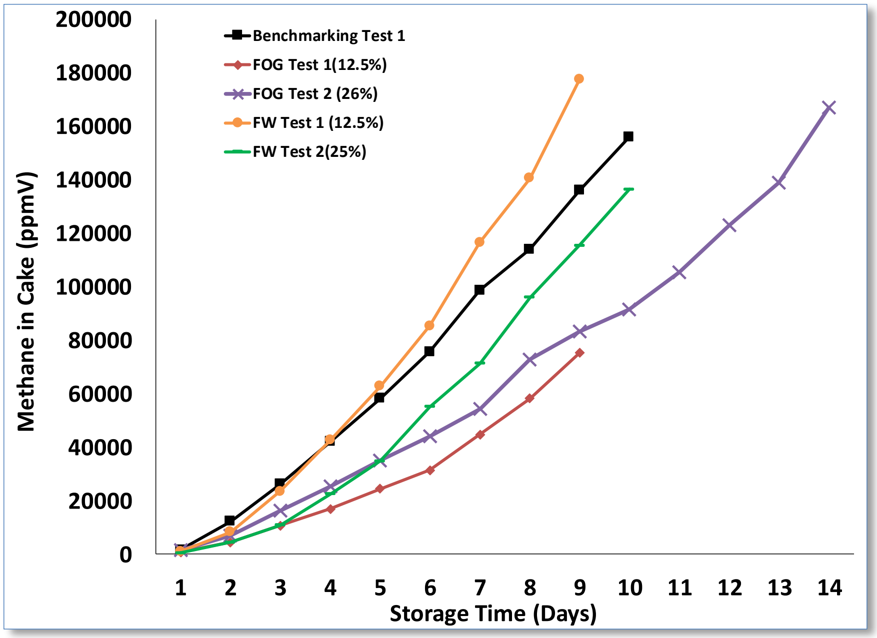
Source: Kennedy/Jenks Consultants

MT concentrations were the highest in FOG Test 2 of all tests. It is possible that the problem associated with ferric chloride dosing during FOG Test 2 contributed to such high MT levels. MT levels in FW Test 2 were 51 percent less than those in FOG Test 2, while MT levels in FW Test 1 were only 15 percent less than those in FOG Test 1. MT concentrations dropped to below detection limits between days 9 and 11 for the two FOG tests.

Both of the FW tests had higher concentrations of the cake odors compared to Benchmarking Test 1. Increases in TVOSCs compared to control (that is, an increase in odor at lower amount of organic waste addition, followed by decrease in odor production at higher organic loading) were observed with several codigestion case studies of source-separated FW, due to synergistic degradation of solids (Higgins and Rajagopalan 2017). At the comparatively lower VS loading of 25 percent FW, increase in odor was exhibited in the results discussed in this section.

In addition to synergistic degradation, reduction of odor-causing compounds by methanogens could also explain the decrease in odor production at higher organic loading. A higher methanogen activity will generally show a decrease in TVOSC production (Higgins et al. 2006). To establish this degradation by methanogens, methane production profiles of the cake were measured. Figure 56 shows the methane concentration measured in the digester cake from each test.

Figure 56: Methane Concentrations in Cake



Source: Kennedy/Jenks Consultants

Methane concentration profiles of the cake solids show that the methane production increased with increasing addition of FW and FOG (FOG Test 2 and FW Test 2). Higher methanogen activity in cake usually is associated with a decrease in VOSC production (Higgins et al. 2006).

The methane production increased at the highest FOG loading in Test 2, but TVOSC concentrations stayed at high ranges. In the case of FW Test 1, the methanogen activity was high and the TVOSC was less than that of FW Test 2. Methanogens may have played an important role in deactivating odor in the case of the higher FW loading.

6.2.7.4 Cation Concentrations and M/D Ratio

To study the effect of monovalent/divalent (M/D) cation ratio on dewatering with FW, samples from each test were analyzed for soluble species of ammonium, sodium, potassium, calcium, and magnesium. The results from these analyses are provided in Table 46.

Table 46: Cation Concentrations in Digester with FOG or FW Addition

Species	Benchmarking Test 1	FOG Test 1	FOG Test 2	FW Test 1	FW Test 2
Sodium (mg/L)	186	214	211	214	226
Potassium (mg/L)	107	128	170	176	186
Magnesium (mg/L)	56	23	3	4	8
Calcium (mg/L)	351	72	44	249	254
Ammonium (mg/L)	1142	1629	1482	1687	1705
Free Ammonia (mg/L)[1]	40	57	52	59	60

[1] **Estimation based on Dig 2 pH in each corresponding test and temp of 35° C (95° F)**

Source: Kennedy/Jenks Consultants

There is a clear trend in concentrations with increasing FW load. Both sodium and potassium levels were 5 percent higher in FW Test 2 than in FW Test 1. The magnesium concentration increased two times between FW tests 1 and 2. Calcium increased about 2 percent and ammonia about 5 percent. The calculated free ammonia concentration was similar in FW Test 2 and FW Test 1.

Compared to the FOG tests with comparable co-waste VS loading, FW 1 contained significantly higher levels of potassium and calcium. Sodium levels did not change. Ammonia only increased by 3 percent. In comparison of FW Test 2 to FOG Test 2, all the cation concentrations increased by various amounts. The most significant increase was that of calcium. The ammonia concentrations increased almost 15 percent with increasing FW addition in FW Test 2. This increase is not significant, not only because the FW in this study had a comparatively lower nitrogen content (2.5 percent), but also due to lower ammonium content in the feed sludges compared to FOG tests (discussed in Section 5.2.3). Due to these low levels in the feed sludge, additional ammonia being released from solids during digestion was likely less. Other studies of source separated FW report nitrogen concentrations of 3.5 percent (Higgins and Rajagopalan 2017).

Higher ammonium concentrations have the potential of causing ammonia toxicity due to free ammonia. Though free ammonia increased by 50 percent between Benchmarking Test 1 and FW Test 2 and by 15 percent between FOG Test 2 and FW Test 2, it was still below the toxicity range (80 to 150 mg N/L), suggesting that the ammonia will not cause inhibition during codigestion of this FW (Parkin and Owen 1986; Garcia and Angenent 2009; Yenigun and Demirel 2013). The synergistic effects of the low nitrogen concentration in this type of FW can help in two ways when codigested with sludge: help in limiting the chances for ammonia toxicity and help in limiting the recycling of nitrogen back to the wastewater treatment processes. Higher ammonium in the digester results in an increase in the ammonium in the centrate streams after dewatering. Such streams are typically recycled back into the plant and contribute to increase in the nitrogen load and subsequent costs for treatment (Higgins and Rajagopalan 2017).

6.2.7.5 Relationship Between M/D Ratio and Dewatering

Using the soluble cation concentrations from Table 46, the M/D ratio was calculated in milliequivalents per liter (meq/L). Table 47 shows the M/D ratio of the FOG tests, as well as Benchmarking Test 1 and FOG tests 1 and 2 for comparison.

Table 47: M/D Ratio Variation Over the FOG Tests

Test	M/D Ratio
Benchmarking Test 1	3.4
FOG Test 1 (12.5%)	18.8
FW Test 1 (12.5%)	8
FOG Test 2 (26%)	39.2
FW Test 2 (25%)	8

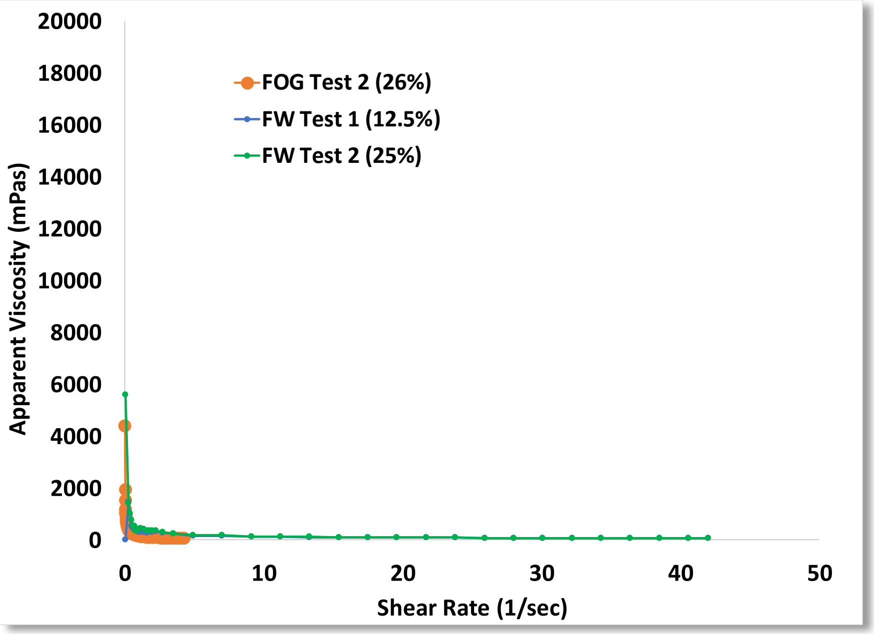
Source: Kennedy/Jenks Consultants

In general, an M/D ratio of less than 10 is considered favorable for dewatering. Benchmarking Test 1 had the lowest and most favorable M/D ratio and exhibited the least polymer demand. In FOG Test 1, the M/D ratio was the lowest of all the FOG tests and exhibited better dewatering when compared to FOG Test 2. Both FW tests had a lower M/D ratio than the FOG tests and a higher ratio than that of Benchmarking Test 1. The polymer demand in both FW tests was higher than that of the corresponding FOG test (See Table 41). However, the dewatered solids percent decreased in FW Test 1 compared to FOG Test 1 and increased in FW Test 2 compared to FOG Test 2. At the same M/D ratio in both FW tests, the dewatering characteristics and the OPD exhibit different trends when compared to FOG tests. With respect to the FW codigestion tests, these findings from the current study indicate that other factors apart from M/D ratio may have affected dewatering. Other studies have found that at M/D ratios between 5 and 40, the cake solids percentage decreased with increasing M/D ratios (Higgins and Rajagopalan 2017).

6.2.8 Digester Rheology and Rapid Volume Expansion (RVE)

The rheology of the digester contents is important to understanding operational difficulties such as RVE or rapid rise foaming. A practical application of rheology measurements is how mixing rate in the digester affects the viscosity, which can likely cause rapid rise foam. This section discusses the results from viscosity and RVE measurements. Figure 57 compares the apparent viscosity profile as a function of shear rate of the available data from FW Tests.

Figure 57: Viscosity and Yield Stress

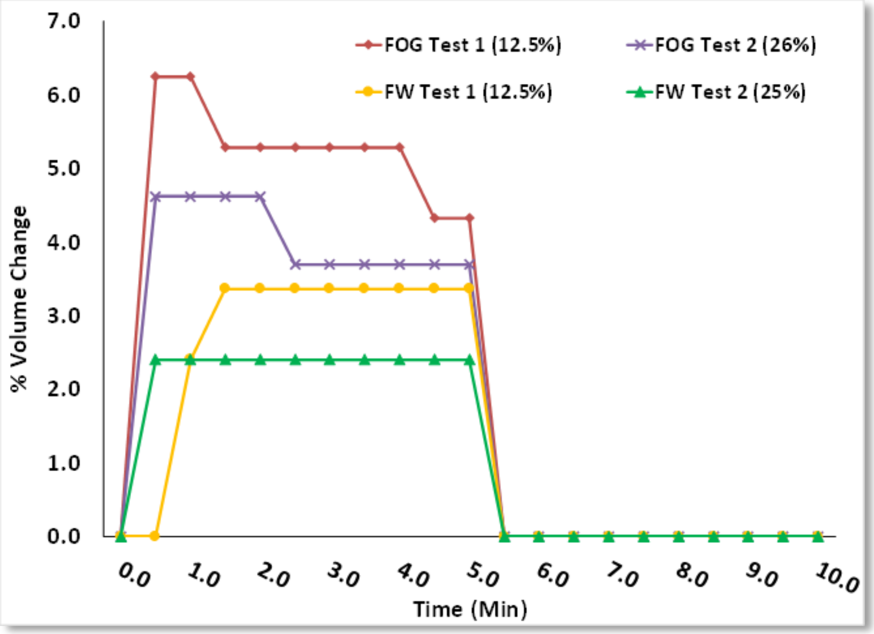


Source: Kennedy/Jenks Consultants

The digested sludge typically behaves as a non-Newtonian fluid with shear thinning behavior (Higgins and Rajagopalan 2017). This is presented in Figure 57 where the shear rate increases, and the viscosity decreases between FOG Test 2 and FW tests. FOG Test 1 viscosity data is not available. The apparent viscosities were not significantly different between them at any given shear rate. It was not possible to determine if codigestion with FW impacted the viscosity.

Viscosity, shear stress, and the RVE are all related to each other. RVE is mainly attributed to gas holdup in digester sludge. In the practical aspect of digester operation, the shear rate is a measure of the mixing. Gas holdup becomes greater as the shear rate in the digester decreases (or in practical scenario, when mixing is suddenly stopped). Viscosity then increases and the digester sludge exhibits yield stress which correlates to volume expansion. Gas produced in the digester becomes entrapped within the solids, resulting in RVE foaming. The RVE was measured (Figure 58) and indicates the change in volume due to foaming and gas holdup.

Figure 58: Rapid Volume Expansion



Source: Kennedy/Jenks Consultants

The changes in the sludge volume during mixing in the various codigestion tests were less than 7 percent. The only significant trend observed was the lower volume expansion with increasing co-waste loading. This suggested that, under such codigestion conditions, with similar characteristics such as the FOG or FW in this study, RVE risk is predicted not to be significant for this digester.

6.3 Summary of FW Codigestion Tests

Results during FW codigestion were evaluated for potential effects on gas production, viscosity, foaming or volume expansion, dewatering, solids production, and cake quality in terms of odors. The main findings of this work are the following:

1. Codigestion using FW increased the unit gas production (cu.ft. gas produced/lb of VS destroyed) in the digesters. Compared to the benchmarking test, the unit gas production in FW Test 1 and FW Test 2 had 6 percent and 14 percent higher unit gas production. The higher unit gas production in FW Test 2 compared to that in FW Test 1 can be attributed to the higher FW VS to sludge VS ratio used in the test. For unit mass (lb) of VS added, FW contributed to higher gas production than sludge due to higher VS reduction and higher unit gas production potential. Table 48 shows a comparison of all the gas production results.

Table 48: Summary of Gas Production, VSR, and Unit Gas Production

Test	Total Gas Production (cu.ft/d)	VSR (%)	Unit Gas Produced (cu.ft./lb VS destroyed)
Benchmarking Test 1 (0.07 lbs VS/ cu.ft.)	141,067	61	15
FOG Test 1 (12.5% FOG)	163,057	64.09	14.47
FOG Test 2 (26% FOG)	217,283	64.27	16.05
FW Test 1 (12.5% FW)	129,163	70	15.8
FW Test 2 (25% FW)	135,866	68	17

Source: Kennedy/Jenks Consultants

2. The methane content of the gas generated during FW Test 1 and Test 2 was similar and the CO_2 content differed marginally (about 1 percent) between the two tests. When compared to Benchmarking Test 1, the methane content was similar to FW Test 1 and only marginally different in FW Test 2. The CO_2 content was higher in the FW 2 tests.
3. The digester gas H_2S concentration in FW Test 2 (82 ppmV) was lower than that in FW Test 1 (142 ppmV), a reduction of 34 percent. However, it is currently not known if the decrease was a direct effect of the added FW or due to potential differences in ferric chloride addition or other differences in the digester operating conditions.
4. For the dewatering results, the polymer demand for both FW tests were comparable (approximately 32 lb/T). Percent cake solids (approximately 20 percent) also were similar between the two tests. Both cake solids and polymer demand were higher than corresponding values for the Benchmarking Test 1. The polymer demand in both FW tests was higher than that of each corresponding FOG test, but the dewatered solids percent decreased in FW Test 1 compared to FOG Test 1 and increased in FW Test 2 compared to FOG Test 2. At the same M/D ratio in both FW tests, the dewatering characteristics and the OPD exhibited different trends when compared to FOG tests. Overall, FW addition improved dewatered cake solids content when compared to FOG codigestion. With respect to the FW codigestion tests, these findings from the current study indicate that factors other than M/D ratio may have affected dewatering. Table 49 shows the dewatering test results.

Table 49: Summary of Dewatering Results

Test	M/D Ratio	Polymer Demand (lbs/DT)	Difference Relative to Benchmarking Test 1 (%)	Dewatered Cake Solids (%)	Difference Relative to Benchmarking Test 1 (%)
Benchmarking Test 1	3.5	28		17.04	
FOG Test 1 (12.5%)	19.6	28.6		21.58	
FOG Test 2 (26%)	41.7	30.75		18.12	
FW Test 1 (12.5%)	8	32.5	13.7 (increase)	20.08	18%
FW Test 2 (25%)	8	32.05	4.3 (increase)	20.09	18%

Source: Kennedy/Jenks Consultants

5. Addition of FW affected cake odor. In general, TVOSCs were higher at higher FW loading and higher than the benchmarking test. They were lower for each FW test compared to the corresponding FOG test.
6. The addition of FW had very little to no effect on digestate viscosity and yield stress.
7. The rapid volume expansion potential (RVE) decreased with increasing FW addition.

CHAPTER 7:
Projected Benefits and Economic Evaluation

This chapter examines the benefits and economic implications of the proposed preprocessing and codigestion techniques for lowering the cost of codigestion and reducing cake solids.

7.1 Approach

The proposed technique for extracting food waste (FW) from municipal solid waste (MSW) and its use as a higher value resource involves two major steps: preprocessing by waste processing facilities and use in codigestion at WWTPs. These processing stages were evaluated separately based on the scenarios described in the following sections. Overall, the main objectives of the economic analysis were to determine:

- Cost effectiveness of OREX in preprocessing FW
- The differential cost/savings of codigestion (compared to sludge-only digestion)
- The payback period for WWTPs investing in FW codigestion
- Effect of factors such as tipping fees, electricity cost, and WWTP size on the economic feasibility of codigestion

Many of the costs, revenues, and savings for preprocessing and codigestion were determined from various waste processing facilities, equipment vendors, the proprietary Kennedy/Jenks (K/J) Waste to Energy (WTE) model, as well as past project experience. However, these estimates are primarily modelled after the expenses, waste quality, and seasonal patterns typically experienced in the San Francisco Bay Area. Detailed evaluations using other site-specific conditions will be required to obtain more reliable cost estimates for a FW-based codigestion program.

7.1.1 MSW Pre-Processing

An economic evaluation was performed for three different scenarios of MSW management. The following cases were considered:

- Direct disposal of MSW to landfills
- Preprocessing of MSW using OREX to extract FW
- Preprocessing of source-separated waste using additional polishing step to extract FW

The benefits and economic evaluation of these preprocessing steps considered methods of waste collection, separation and polishing technique employed at the waste processing facility, hauling and disposal fees to landfills, and delivery and tipping fees to WWTPs. Capital and operating costs were annualized and compared on a per ton basis (of MSW). The objective of this evaluation was to compare the advantages/disadvantages of OREX preprocessing to other commonly used separation and FW extraction processes.

7.1.2 Codigestion at WWTPs

Codigestion at WWTPs compared different FW loading ratios to no FW loading. Three different digestion loading conditions were analyzed, based on a 15 MGD and 100 MGD WWTP size. The following cases were considered:

- Sludge-only digestion
- Codigestion at 12.5 percent FW VS to sludge VS ratio
- Codigestion at 25 percent FW VS to sludge VS ratio

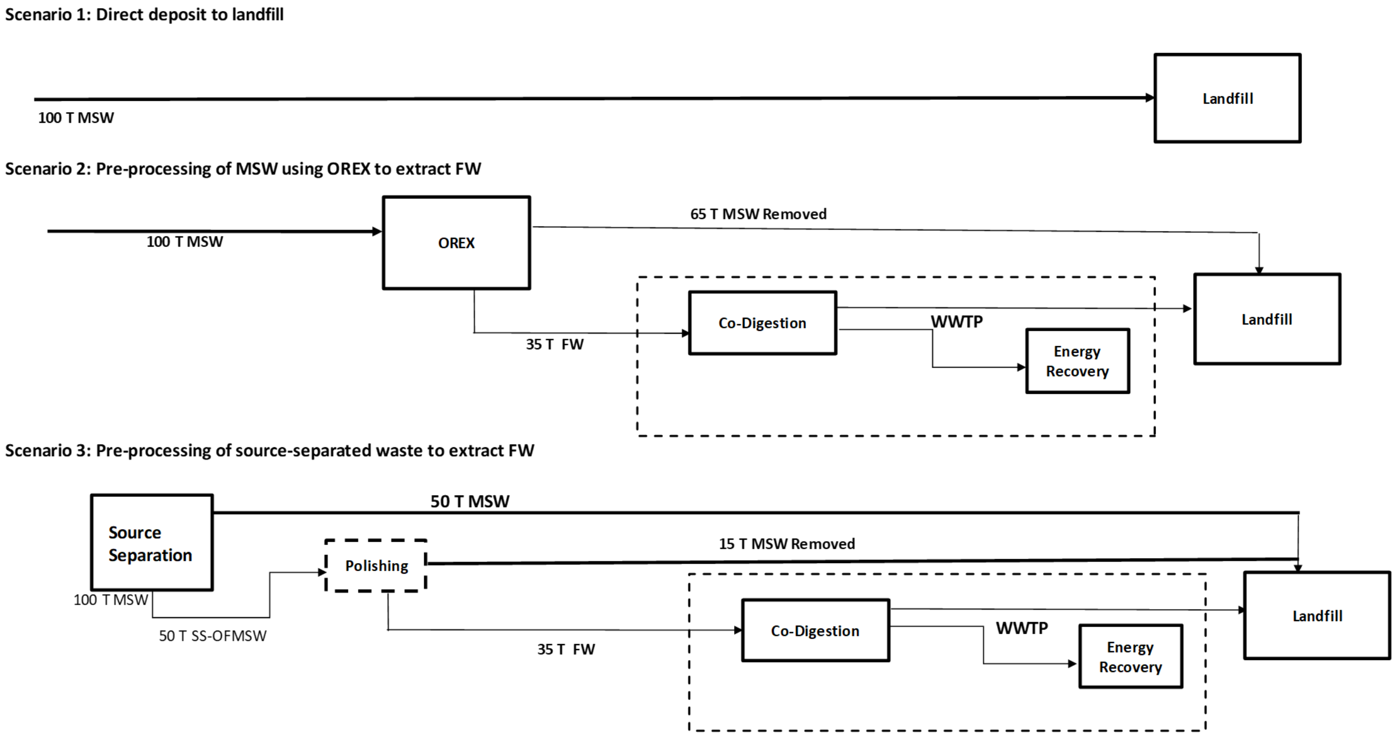
For each case, differential costs for FW codigestion were calculated against costs of sludge-only digestion. This included capital costs for installing/retrofitting a FW receiving station, purchasing a paddle finisher, and the necessary gas cleaning and cogeneration equipment for expanding gas production capacity. Operating and maintenance (O&M) costs consisted of running the FW receiving and polishing station, biogas cleaning and cogeneration, downstream processing (such as polymer costs for dewatering and hauling costs for cake disposal), and digester operation. Additional savings in energy recovery and revenue from tipping fees for received FW were also considered in the economic analysis for WWTPs. Many of the operating costs and savings used in this analysis are generated based on the results obtained throughout this study, which was then scaled up to larger WWTP sizes. A sensitivity analysis was performed to account for the potential variation in tipping fees and electricity prices that could be experienced by other WWTPs.

7.2 MSW Pre-Processing Economic Analysis

7.2.2 MSW Pre-Processing Scenarios

The preprocessing technique used for this study (extraction of FW using OREX equipment at Recology) was compared to two other scenarios for waste management. These cases are described in more detail and depicted in Figure 59.

Figure 59: Process Flow Diagram of Pre-Processing Scenarios at Waste Processing Facilities



The steps (in dashed outlines) depict the processes that take place at WWTPs and are not included in the scope of the analysis for FW preprocessing

Source: Kennedy/Jenks Consultants

The steps (in dashed outlines) in Figure 59 depict the processes that take place at WWTPs and are not included in the scope of the analysis for FW preprocessing (they are discussed in Section 7.3). A basis of 100 ton (T) of incoming co-mingled MSW was considered for each scenario and the processes being evaluated are described in more detail:

1. Base case – Direct disposal of MSW to landfills
   - In the absence of any preprocessing methods to increase the beneficial use of the end product (FW), it is assumed that all of the waste collected is disposed of at landfills.
2. Preprocessing of MSW using OREX to extract FW
   - Out of the 100 T of MSW processed by OREX, 35 T of FW is extracted. The remaining 65 T are hauled to a landfill for disposal. This scenario represents the preprocessing method proposed in this study.
3. Preprocessing of source-separated waste using additional polishing step to extract FW
   - The collected waste was source-separated and is assumed to have brought in 50 T of source-separated organic fraction of MSW (SS-OFMSW). The remaining 50 T is disposed of at landfills. The 50 T of SS-OFMSW is processed further at the waste processing facility, separating 35 T of FW using a polishing unit. The 15 T of removed contaminants is also hauled to landfills.

- The estimates and assumptions used for this analysis are selected based on this research team's demonstration study data and discussions with industry experts.

7.2.2 MSW Pre-Processing System Assumptions

The economic analysis for MSW preprocessing at waste processing facilities considered the treatment of 100 T of MSW. Table 50 and Table 51 list the system assumptions used to perform this analysis, including equipment performance, operating parameters, and equipment costs.

Table 50: System Assumptions for Pre-Processing at Waste Processing Facilities

Pre-Processing System Assumptions	Values
Quantity of total collectable MSW	100 T
Hauling and disposal cost to landfill	25 to 75 \$/T (75\$ assumed as base-case)
Hauling cost to WWTP	75 \$/hr for 4 hours for 20 T
Extractable FW from MSW by OREX	35 %
OREX full-size operating capacity	800 TPD of MSW (250 TPD of FW produced)
OREX operating costs[1]	7 \$/T
Extractable SS-OFMSW from MSW	50 %
Polishing unit full-size operating capacity	250 TPD of FW produced
Polishing unit operating costs[1]	6 \$/T
Extractable FW from SS-OFMSW	70 %
Preprocessing operating hours	8 hr/day, 365 days/year
Tipping fee paid to WWTP	30\$/T of FW

Source: Kennedy/Jenks Consultants

Table 51: System Assumptions for Equipment Costs at Waste Processing Facilities

Equipment	Costs
OREX equipment cost	\$10,000,000
Polishing equipment cost	\$2,740,000
Installation costs	20% of equipment cost
Miscellaneous costs	20% of equipment cost
Amortization	5% over 25 years

[1] Based on estimates provided by equipment vendor. This value includes costs for fuel and parasitic power consumption, operational and maintenance labor, cost for parts, and contingency mark-ups.

Source: Kennedy/Jenks Consultants

7.2.3 MSW Pre-Processing Economic Analysis Results

The capital costs for the three preprocessing scenarios are summarized in Table 52. Table 53 shows the O&M costs of each preprocessing method as well as the capital costs of the project, converted to a per ton basis for comparison.

Table 52: Capital Costs for Pre-Processing at Waste Processing Facilities

Description	**Scenario 1: Direct Landfill Deposit**	**Scenario 2: OREX Preprocessing**	**Scenario 3: Source Separation and Polishing**
Required preprocessing equipment	—	OREX	Other polishing unit
Equipment cost ($)	—	10,000,000	2,740,000
Installation cost ($)	—	2,000,000	548,000
Miscellaneous costs ($)	—	2,400,000	658,000
Total equipment capital costs ($)	—	14,400,000	3,946,000
Amortized capital cost ($/yr)	**—**	**1,022,000**	**280,000**

Source: Kennedy/Jenks Consultants

Table 53: Combined Capital and Operating Costs Per Ton of MSW Collected

Description	**Scenario 1: Direct Diversion to Landfill**	**Scenario 2: OREX Preprocessing**	**Scenario 3: Source Separation and Polishing**
Collection of MSW ($/T)	—	—	—
Collected of Source Separated Waste ($/T)	—	—	75
Preprocessing capital cost ($/T)	—	3.50	0.96
Preprocessing operating cost ($/T)[1]	—	7	1.25
Hauling and disposal at landfills ($/T)	75	48.75	48.75
Hauling to WWTP ($/T)	—	5.25	5.25
Tipping fee to WWTP ($/T)	—	10.50	10.50
Total cost of waste processing ($/T)	**75**	**75**	**140.60**

Costs for operating the OREX or polishing unit

Source: Kennedy/Jenks Consultants

Results from this economic analysis showed that the total cost to waste processing facilities for extracting FW from MSW was $75/T for OREX preprocessing (Scenario 2) and approximately $140/T for preprocessing that uses source-separation (Scenario 3). Even though the capital costs for source-separation preprocessing were significantly lower than that of OREX (Table 52), the overall cost of OREX preprocessing was more competitive (Source: Kennedy/Jenks Consultants

Table 53: Combined Capital and Operating Costs Per Ton of MSW Collected). The cost of OREX preprocessing is comparable to the base-case of direct landfill disposal ($75/T), with the added benefits of diversion of organic material from landfills and generation of alternate energy. It is possible that under certain circumstances the cost of direct landfill may be lower than that for food waste extraction by OREX (or other) technologies. These scenarios are discussed as part of a sensitivity analysis in the following section.

7.2.4 MSW Preprocessing Sensitivity Analysis

A sensitivity analysis was performed for landfill disposal costs, which can vary for urban, rural, or smaller communities. A single input parameter was varied while keeping all other inputs at the base-case values discussed earlier. Table 55 summarizes how the total cost of waste preprocessing varied depending on changing hauling and landfill disposal fees.

Table 54: Total Cost of Waste Pre-Processing With Changing Landfill Disposal Fees

Hauling and Disposal at Landfills ($/T)	Total Cost of Waste Preprocessing ($/T)		
	Scenario 1: Direct Diversion to Landfill	Scenario 2: OREX Preprocessing	Scenario 3: Source Separation and Polishing
25	25	42.50	108.10
50	50	58.75	124.35
75	75	75	140.60

Source: Kennedy/Jenks Consultants

Results from Table 55 showed that OREX preprocessing costs were lower than the source-separation operating costs, irrespective of landfill tipping fees. When compared to direct disposal costs, OREX preprocessing was a competitive option only if landfill tipping fees were greater than $75/T. This scenario was developed assuming a $30/T of tipping fees to WWTPs for the extracted FW (discussed in the following sections). With lower WWTP tipping fees, OREX preprocessing becomes even more competitive, while higher WWTP tipping fees will make direct disposal preferable. But direct disposal will not provide the additional environmental benefits of organic waste diversion from landfills and energy generation. For optimal benefits to the pre-processors, the tipping fees set by the WWTPs will have to consider the economics of the FW preprocessing.

7.3 Economic Analysis for Codigestion at WWTPs

This economic analysis studied the use of FW in codigestion at WWTPs based on the proposed method in this study. The economic benefits and feasibility of this method was evaluated for two different plant sizes, 15 MGD and 100 MGD. Cost estimates for equipment purchase, O&M

costs related to the digester, introducing co-wastes, biogas generation, and other downstream processing of produced biosolids were included in the scope of this economic analysis.

7.3.1 Codigestion Scenarios

Three operating scenarios for the WWTP digestion system were used. These cases are described in more detail:

1. Base case – Sludge-only digestion (Scenario 1)
    a. Under this scenario it is assumed that the wastewater sludge generated at a 15 or 100 MGD WWTP is anaerobically digested. The generated biogas is cleaned and used for cogeneration. The digested sludge is dewatered and hauled for disposal. Results from Benchmarking Test 1 (Chapter 4) were used to develop the assumptions for cost estimation under this scenario.
2. Codigestion with 12.5 percent FW VS to sludge VS ratio (Scenario 2)
    a. Under this scenario FW received from the off-site waste processing facility is further polished on site, using a paddle finisher. The diluted and polished FW is then fed to the digesters, in addition to the influent sludge produced at the WWTP. Codigestion is performed at the target VS ratio. Biogas cleaning and cogeneration, as well as downstream biosolids treatment and disposal, are similar to the base case described in Scenario 1. Results from FW Test 1 (Chapter 6) were used to develop the assumptions for this scenario.
3. Codigestion with 25 percent FW VS to sludge VS Ratio (Scenario 3)
    a. This scenario is very similar to Scenario 2, except that the target FW loading in increased to maintain a FW to sludge VS ratio of 25 percent. All other operating parameters are similar to the case described in Scenario 2. Results from FW Test 2 (Chapter 6) were used to develop the assumptions for this scenario.

7.3.2 General WWTP Operations Assumptions

General system assumptions that apply to the economic analysis performed on both small- (15 MGD) and large-scale (100 MGD) WWTPs are listed in Table 55.

Table 55: General Assumptions for WWTPs

WWTP Parameter[1]	Assumption
Hourly wage of operators	40$/hr
Polymer cost (for dewatering)	3.3 $/lb
Ferric chloride cost (38% solution as $FeCl_3$)	1.35 $/gallon
FW receiving and polishing station energy consumption	5.4 kWh/T of FW received
Biogas conversion rate of cogeneration engines	20 cu.ft. biogas/kWh
Cost of cogeneration engine O&M	15.08 $/hr-run
Biogas flow rate for Cogeneration	426,800 cu.ft/d
Price of electricity	0.10 to 0.22 $/kwh (0.14$/kWh assumed as base-case)
Range of expected tipping fee rates	20–50 $/T (30$/T assumed as base-case)
Biosolids disposal fee	50–110 $/WT (110$/WT assumed as base-case)

[1] **These assumptions are based on typical conditions for SVCW/San Francisco/ Bay Area**

Source: Kennedy/Jenks Consultants

Other assumptions which will be affected by the size of the WWTP, such as equipment costs, sludge hauling, flows, and FW loadings, are described more specifically in the following section.

7.3.3 Codigestion Scenario-Specific Assumptions

Table 56 shows the plant flow rate and sludge production assumptions used for cost analyses. Table 57 lists the scenario-specific operating parameters based on the performance observed throughout this study for sludge-only digestion and FW codigestion (chapters 4 and 6). Results from the demonstration study that were extrapolated for the cost analyses for full-scale plant operation are shown side-by-side for the 15 MGD and 100 MGD WWTPs. It is important to note that these values (particularly for digester operating costs) are used to compare codigestion conditions to the benchmark. Therefore, some values only capture the relative cost difference and cannot be taken as the absolute O&M costs.

Table 56: Plant Flow Rates and Sludge Production Estimates

System Parameter	System Assumption	
Plant size	15 MGD	100 MGD
Average daily sludge influent to digesters	96,900 gpd	646,000 gpd

Source: Kennedy/Jenks Consultants

Table 57: Assumptions for 15 MGD and 100 MGD Plant Operations Data From Demonstration Study Results

	Scenario 1: Sludge-only Digestion		Scenario 2: FW Loading at 12.5% VS Ratio		Scenario 3: FW Loading at 25% VS Ratio	
	15 MGD	100 MGD	15 MGD	100 MGD	15 MGD	100 MGD
Digester performance						
Influent Sludge VS[1] (lb VS/d)	40,000	266,700	40,000	266,700	40,000	266,700
Influent FW VS[1] (lb VS/d)	—		5,000	33,300	10,000	66,700
VSR[2] (%)	56.6		69.9		67.7	
Gas production						
Unit gas production[2] (cu.ft. biogas/lb)	15		15.8		17	
Total produced gas[1] (cu.ft./d)	339,800	2,265,300	496,500	3,310,400	576,000	3,839,700
Methane content (%)	59.5		59.5		59.8	
Gas cleaning						
Biogas H_2S Content[2] (ppm)	120		124		87	
H_2S content was assumed to be equal in the evaluated scenarios. Biogas cleaning costs were assumed to be proportional to gas production.[3]						
Dewatering performance						
OPD required[2] (lb/DT)	28		32.50		32.05	
Average cake solids (TS%)[2]	17.04		20.8		20.09	
Dry ton of cake produced (DT/yr)[1]	1,310	8,760	810	5,430	730	4,870
Biosolids to be disposed (WT/yr)[1]	7,710	51,410	4,050	27,020	3,630	24,240

[1] Study conditions extrapolated for 15 MGD / 100 MGD plant.

[2] Directly based on study results: 3.6 DT/day for Benchmarking Test 1; 2.23 DT/day for FW Test 2 and 0.2 DT/day for FW Test 2.

[3] Costs include H_2S SULFATREAT treatment and GAC for siloxane removal.

Source: Kennedy/Jenks Consultants

Table 58 lists the labor hours (in full-time equivalent units – FTE) needed for each operating process. For digester operation, the differential labor hours for codigestion (compared to sludge-only digestion) are listed.

Table 58: Operating Conditions for Evaluated Scenarios Based on WWTP Size

	Scenario 1 Sludge-only Digestion		**Scenario 2 FW Loading at 12.5% VS Ratio**		**Scenario 3 FW Loading at 25% VS Ratio**	
	15 MGD	**100 MGD**	**15 MGD**	**100 MGD**	**15 MGD**	**100 MGD**
Digestion						
Mixing	Continuous		Unchanged		Unchanged	
Labor[1] (FTE)	—	—	0.025	0.167	0.025	0.167
Gas cleaning						
Labor (FTE)	0.5	3.3	0.5	3.3	0.5	3.3
Cogeneration						
Labor (FTE)	1	3	1	3	1	3
Dewatering						
Labor (FTE)	0.4	2.67	0.4	2.67	0.4	2.67

[1] **Based on additional labor needed for codigestion, compared to sludge-only digester operation**

Source: Kennedy/Jenks Consultants

Table 59 lists the capital cost assumptions for the FW receiving, polishing station, and cogeneration. For the purposes of this economic analysis, it was assumed that the WWTP typically flares any produced biogas from its digestion process and will need to establish gas cleaning and cogeneration to use the potential energy savings. Costs for any digester improvement were not included, as it was assumed that the WWTPs have sufficient (or excess) digester capacity.

Table 59: Capital Cost Assumptions

System Component	System Assumption
FW Receiving and Polishing Station	
Units required per item	1 for 15 MGD, 2 for 100 MGD plant
Equipment cost (paddle finisher)	$62,000/unit
Equipment cost (mixer)	$40,000/unit
Chopper pump (to paddle finisher)	$40,000/unit
Transfer pump (to digester)	$75,000/100 gpm unit
Receiving station structural costs (sub-ground pit and high-performance coatings)	$500,000 for first pit, scaling up 1.5x for additional pit
Poly tank for polished solids	1 unit per paddle finisher, approximately 3000 gal capacity
Installation cost	30% of total specialized equipment costs
Miscellaneous cost	20% of total equipment and installation costs
Cogeneration	
Units required	2 units for all scenarios in 15 MGD plant, 7,10, and 12 units for Scenario 1, 2, and 3 in 100 MGD plant, respectively
Equipment cost	$672,000 /unit
Installation cost	20% of equipment cost
Client administration and legal costs	25% of equipment and installation costs
Contingency costs	45% of equipment and installation costs

Source: Kennedy/Jenks Consultants

7.4 Codigestion at 15 MGD WWTP

This section summarizes the results of the economic analysis conducted for a small plant (annual average flow of 15 MGD).

7.4.1 Results

The economic analysis for the 15 MGD plant evaluated the annualized capital costs, O&M costs, the potential revenue streams from tipping fees, and the energy recovery savings for each scenario. The annual savings in operating costs for the FW codigestion was compared to the sludge-only digestion condition, and a payback period of the initial investment amount was determined. A sensitivity analysis was then performed to assess the effect of changing electricity prices, tipping fees, and biosolids disposal costs. These results are discussed in more detail in the following sections.

7.4.1.1 Capital Costs

Table 60 summarizes the capital costs for implementing biogas recovery and codigestion capacity at WWTPs.

Table 60: Capital Costs for 15 MGD WWTP

	Scenario 1 Sludge-only Digestion	Scenario 2 FW Loading at 12.5% VS Ratio	Scenario 3 FW Loading at 25% VS Ratio
FW Receiving and Polishing Station ($)	—	869,700	869,700
Gas Cleaning ($)	707,900	1,034,500	1,199,900
Required IC Capacity ($)	2,741,800	2,741,800	2,741,800
Total capital costs ($)	3,449,700	4,646,000	4,811,400
Total Amortized Capital Cost[1] ($/yr)	**244,900**	**329,900**	**341,600**

[1] **Amortized over 25 years at rate of 5 percent.**

Source: Kennedy/Jenks Consultants

As listed in Table 5959, capital costs for setting up the FW receiving and polishing station includes equipment costs for the paddle finisher, mixer, polyethylene tank (to hold polished solids), and the chopper and transfer pumps used to convey the FW slurry to the paddle finisher and digester. Relevant installation (at 20 to 30 percent of equipment cost) and miscellaneous (at 20 percent of equipment and installation cost) were also included.

Gas cleaning costs were based on a $600,000 estimate for a base system that can treat 200 cfm of biogas. This price was proportionally scaled up for larger biogas flowrates. Cost and number of units of internal combustion (IC) engines were calculated using the Kennedy/Jenks WTE model, based on the Waukesha engine (750 kW) performance.

7.4.1.2 Operating and Maintenance Costs

Table 61lists the relative O&M costs related to the digestion and downstream processing necessary for each scenario.

Table 61: Operating Costs for 15 MGD Plant

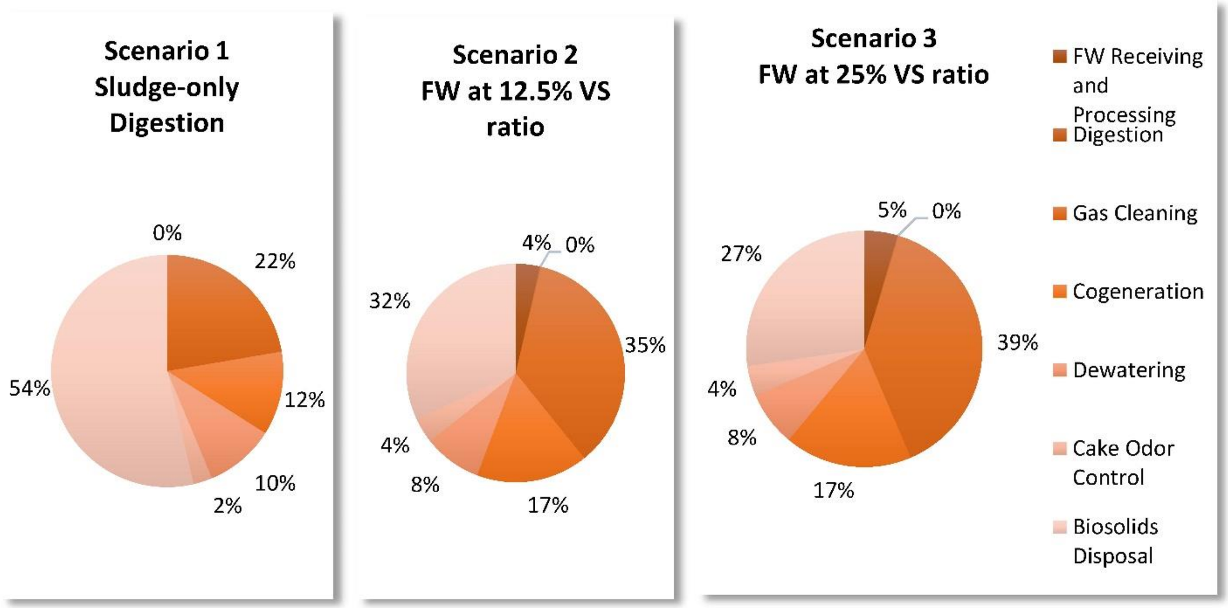
	Scenario 1 Sludge-only Digestion	**Scenario 2 FW Loading at 12.5% VS Ratio**	**Scenario 3 (FW loading at 25% VS ratio)**
FW Receiving and Processing Station			
Total labor costs ($/yr)	—	33,300	33,300
Total equipment operating costs ($/yr)	—	16,900	33,800
Total O&M costs ($/yr)	**—**	**50,200**	**67,100**
Digestion			
Total additional O&M costs ($/yr)	**—**	**2,100**	**2,100**
Gas cleaning			
Total chemical costs ($/yr)	142,100	207,700	240,900
Total labor costs ($/yr)	41,600	41,600	41,600
Total equipment operating costs ($/yr)	171,700	250,900	291,000
Total O&M costs ($/yr)	**355,400**	**500,200**	**573,500**
Cogeneration			
Total equipment operating costs ($/yr)	102,800	150,200	174,200
Total labor costs ($/yr)	83,200	83,200	83,200
Total O&M costs ($/yr)	**186,000**	**233,400**	**257,400**
Dewatering			
Total polymer costs ($/yr)	121,413	87,296	77,208
Total labor costs ($/yr)	33,300	33,300	33,300
Total O&M costs ($/yr)	**154,700**	**120,600**	**110,500**
H_2S Control			
Total $FeCl_3$ costs ($/yr)	**42,100**	**53,700**	**61,200**
Biosolids Disposal			
Total disposal costs ($/yr)	**854,700**	**449,300**	**402,800**
Net O&M Costs			
Net costs ($/yr)[1]	**1,592,900**	**1,409,400**	**1,474,500**

[1] **Calculated relative to benchmark operation. Not to be used as absolute plant O&M costs.**

Source: Kennedy/Jenks Consultants

Figure 60 depicts the cost breakdown for each step of the process.

Figure 60: O&M Costs Breakdown for 15 MGD



Source: Kennedy/Jenks Consultants

Results from Figure 60 show that digestion costs account for almost 0 percent of the O&M costs. As stated in Section 7.3.3, this is because digester costs were calculated relative to benchmark operation (Scenario 1), and therefore, depict the differential increase in operating costs due to FW codigestion. Biosolids disposal costs, however, account for a large portion of the relative O&M costs calculated for the WWTP (at 27 to 54 percent), followed by gas cleaning costs. The biosolids removal costs were reduced for increasing FW loadings. This was reflected in the relative O&M costs, which decreased for FW codigestion. While sludge-only digestion had the highest comparative O&M cost, 12.5 percent FW loading (Scenario 2) had the lowest. Table 62 summarizes the revenue streams and energy saving potential for the different operating scenarios.

Table 62: Revenue and Energy Savings

	Scenario 1 (Sludge-only Digestion)	**Scenario 2 (FW Loading at 12.5% VS ratio)**	**Scenario 3 (FW Loading at 25% VS ratio)**
Tipping Fee Revenue			
Total FW received (TPD)	—	8.6	17.2
Total revenue from receiving FW ($/yr)	—	**93,900**	**187,800**
Energy Recovery			
Total energy produced (kWh/d)	17,000	24,800	28,800
Total energy recovery savings ($/yr)	**868,200**	**1,268,700**	**1,471,600**

Source: Kennedy/Jenks Consultants

At a FW receival rate of 17.2 TPD, Scenario 3 (25 percent FW loading) offers the highest revenue potential from tipping fees. At the base-case rate of $30/T, Scenario 2 can obtain $93,900 of revenue per year, while Scenario 3 can obtain $187,800 per year. This revenue stream does not apply to the sludge-only scenario. Based on the biogas production potential of each operating condition, the total energy recovery savings were also calculated to be $868,200, $1,268,700, and $1,471,600 for scenarios 1, 2, and 3, respectively.

7.4.1.3 Net Costs and Savings for Codigestion

The overall capital and O&M costs, energy savings, and tipping fee revenues were combined to determine the net spending for WWTPs. These values are compared only among each other, as some of them were calculated as relative costs. The payback period for implementing the FW codigestion and biogas recovery program was calculated based on the savings generated by the novel processing method (compared to the base-case operating scenario of digesting only sludge). These results are listed in Table 63.

Table 63: Net Spending and Payback Period for 15 MGD Plant

	Scenario 1 Sludge-only Digestion	**Scenario 2 FW Loading at 12.5% VS Ratio**	**Scenario 3 FW Loading at 25% VS Ratio**
Net Savings or Expenses			
Total annualized capital costs ($/yr)	244,900	329,900	341,600
Total O&M costs ($/yr)	1,592,800	1,409,400	1,474,500
Total savings from energy recovery ($/yr)	868,200	1,268,700	1,471,600
Total revenue from tipping fees ($/yr)	—	93,900	187,800
Net savings (expenses)	**(969,700)**	**(376,700)**	**(156,700)**
Savings compared to sludge-only digestion	—	**593,000**	**812,900**
Payback Period			
Total capital investment	3,449,700	4,646,000	4,811,400
Payback period	—	**7.8**	**5.9**

Source: Kennedy/Jenks Consultants

As stated in Section 7.3.3, O&M costs and the net saving/expenses to the WWTP were not taken as an absolute value. They were used to perform a comparison between the FW codigestion condition and the benchmark. In this case, the addition of FW codigestion resulted in an estimated annual savings of $593,000 (Scenario 2) and $812,900 (Scenario 3) compared to the digester being operated without any FW. These savings result in a payback period of either 7.8 years or 5.9 years for scenarios 2 and 3, respectively. Therefore, it is more beneficial for WWTPs to implement FW codigestion program at the higher 25 percent VS loading. While 12.5 percent FW loading had the lowest O&M costs, it could not account for the increased biogas production and FW tipping fees provided by the higher loadings. These revenue streams were calculated based on the base-case electricity price of 0.14/kWh and tipping fees of $30/T. Variation in these values is further discussed below.

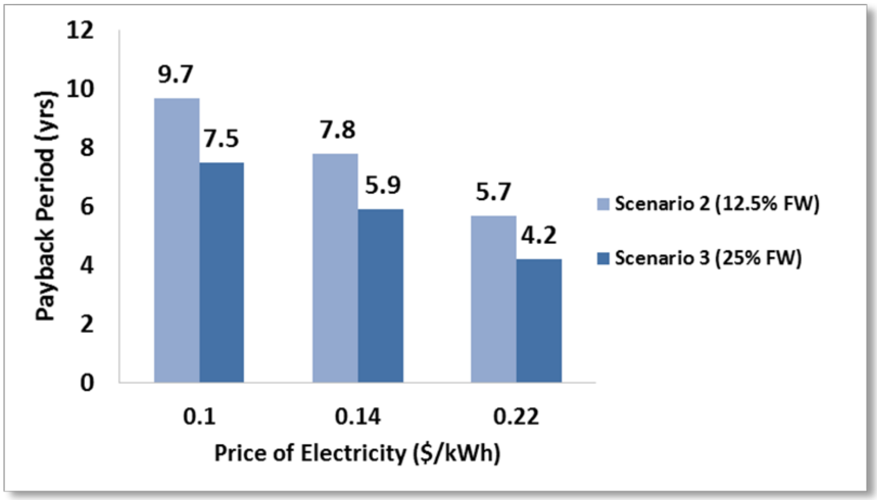
7.4.2 Codigestion Sensitivity Analysis

Sensitivity analyses were performed for the two savings- or revenue-generating variables: the price of electricity and the tipping fee. A sensitivity analysis was also performed on the cost of disposal for the produced digester cake. A single input parameter was varied while keeping all other inputs at the base-case values discussed earlier. The following two subsections discuss how each variable affected the expected payback period for the codigestion projects.

7.4.2.1 Changes in Unit Electricity Price

The base-case electricity price used in the economic analysis was 0.14 $/kWh. Figure 61 shows how the expected payback period for the codigestion project (scenarios 2 and 3) changed as unit electricity price decreased to $0.10/kWh or increased to $0.22/kWh.

Figure 61: Electricity Price Sensitivity Analysis



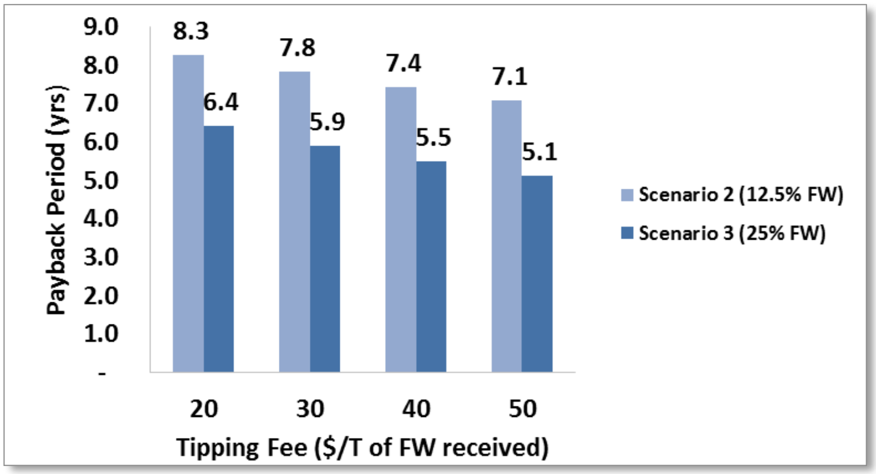
Source: Kennedy/Jenks Consultants

At $0.10/kWh, Scenario 2 (12.5 percent FW VS loading) is predicted to achieve a payback period of about 10 years, while a higher loading of FW in Scenario 3 (25 percent FW VS loading) could achieve a payback period of about 7.5 years. At $0.22/kWh (a price similar to that paid by SVCW), Scenario 2 achieved an estimated payback period of about 6 years and Scenario 3 resulted in payback within 4.5 years. Therefore, the incentive to establish a codigestion program increases in locations with higher electricity prices. This sensitivity analysis also shows that increasing FW loading can result in faster payback on the WWTP`s capital investment.

7.4.2.2 Changes in Tipping Fee

The introduction of FW to the digester presents a new revenue stream for WWTPs through a tipping fee of about $20 to $50/ton of FW received. The effect of this variation on the expected payback period for the codigestion project is summarized in Figure 62.

Figure 62: Tipping Fee Sensitivity Analysis



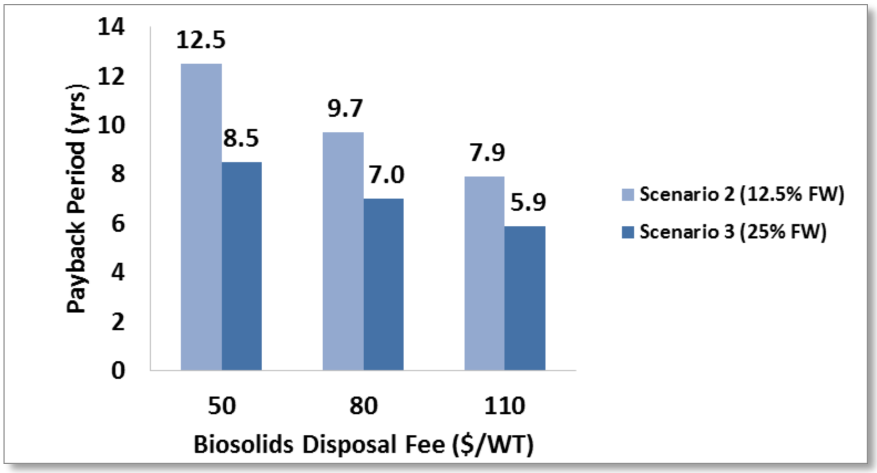
Source: Kennedy/Jenks Consultants

The base-case value for tipping fees was taken at $30/T, which resulted in a payback period of about eight or six years (for scenarios 2 and 3, respectively). As the tipping fee decreased to $20/T, the payback period slightly increased to 8.5 and 6.5 years, while increasing tipping fees were predicted to result in much faster payback periods for the project. At $50/T, a payback period of seven years or five years was predicted for FW loadings of scenarios 2 and 3, respectively.

7.4.2.3 Changes in Biosolids Disposal Fees

Another important factor in the overall operating costs of the WWTP is the cost of disposal for the produced digester cake. The effect of these changes on the payback period is summarized in Figure 63.

Figure 63: Biosolids Disposal Costs Sensitivity Analysis



Source: Kennedy/Jenks Consultants

The base-case value for biosolids disposal fees was taken at $110/T, which resulted in a payback period of about eight or six years (for scenarios 2 and 3, respectively). This value represents the high rates paid by SVCW, but the cost of biosolids disposal produced from the digester may be lower in other areas. As the disposal fee decreased to $80/T, the payback period was estimated to be 10 or 7 years. A further drop in disposal fees resulted in a predicted payback period of 12.5 or 8.5 years for scenarios 2 and 3, respectively.

7.5 Codigestion at 100 MGD WWTP

This section summarizes the results of the economic analysis conducted for a larger plant (annual average flow of 100 MGD).

7.5.1 Results

The economic analysis for the 100 MGD plant evaluated the annualized capital costs, relative O&M costs, the potential revenue streams from tipping fees, and the energy recovery savings for each scenario. The relative savings in operating costs for the FW codigestion was compared to the sludge-only condition, and a payback period of the initial investment was determined. A sensitivity analysis was then performed to assess the effect of changing electricity prices, tipping fees, and biosolids disposal costs on this value. These results are discussed in more detail in the following sections.

7.5.1.1 Capital Costs

Table 64 summarizes the capital costs for implementing biogas recovery and codigestion capacity at WWTPs.

Table 64: Capital Costs for 100 MGD WWTP

	Scenario 1 Sludge-only Digestion	Scenario 2 FW Loading at 12.5% VS Ratio	Scenario 3 FW Loading at 25% VS Ratio
FW Receiving and Polishing Station ($)	—	1,489,400	1,489,400
Gas Cleaning ($)	4,719,300	6,896,600	7,999,500
Required IC Capacity ($)	9,596,200	13,708,800	16,450,600
Total capital costs ($)	14,315,500	22,094,800	25,939,400
Total Amortized Capital Cost[1] ($/yr)	**1,016,400**	**1,568,700**	**1,841,700**

[1] Amortized over 25 years at rate of 5 percent.

Source: Kennedy/Jenks Consultants

The cost for setting up the FW receiving and polishing station for the larger volumes needed at 100 MGD includes equipment costs for two parallel processes. This includes the paddle finisher, mixer, poly tank (to hold polished solids), and the chopper and transfer pumps. The presence of a second parallel receiving and polishing stream ensures that the flow of FW to the codigesters can be maintained even in the event of a disabled unit.

Similar to the 15 MGD case, it was assumed that the WWTP will need to establish gas cleaning and cogeneration to use the potential energy recovery savings. Gas cleaning costs were proportionally scaled up based on the biogas flowrates. Cost and the number of required units for the internal combustion (IC) engines were calculated using the Kennedy/Jenks WTE model, based on the Waukesha engine (750 kW) performance.

7.5.1.2 Operating and Maintenance Costs

Table 65 lists the O&M costs related to the digestion and downstream processing necessary for each scenario. Digester operating cost is listed as the relative increase from the benchmark, due to codigestion.

Table 65: Operating Costs for 100 MGD Plant

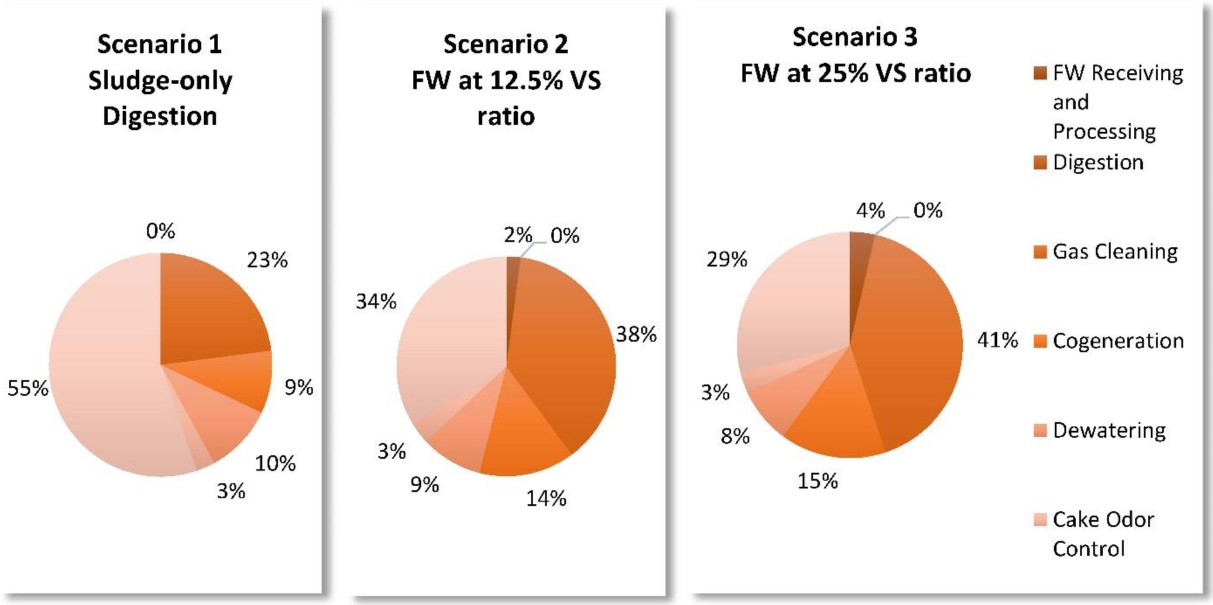
	Scenario 1 Sludge-only Digestion	Scenario 2 FW Loading at 12.5% VS Ratio	Scenario 3 FW Loading at 25% VS ratio
FW Receiving and Polishing Station			
Total labor costs ($/yr)	—	66,600	99,800
Total equipment operating costs ($/yr)	—	112,700	225,300
Total O&M costs ($/yr)	**—**	**179,200**	**325,100**
Digestion			
Total additional O&M costs ($/yr)	**—**	**13,900**	**13,900**
Gas cleaning			
Total chemical costs ($/yr)	947,400	1,384,500	1,605,900
Total labor costs ($/yr)	277,300	277,300	277,300
Total equipment operating costs ($/yr)	1,144,600	1,672,600	1,940,100
Total O&M costs ($/yr)	**2,369,300**	**3,334,400**	**3,823,300**
Cogeneration			
Total equipment operating costs ($/yr)	685,100	1,001,100	1,161,200
Total labor costs ($/yr)	249,600	249,600	249,600
Total O&M costs ($/yr)	**934,700**	**1,250,700**	**1,410,800**
Dewatering			
Total polymer costs ($/yr)	809,400	581,900	514,700
Total labor costs ($/yr)	221,900	221,900	221,900
Total O&M costs ($/yr)	**1,031,200**	**803,800**	**736,500**
Cake Odor Control			
Total $FeCl_3$ costs ($/yr)	**280,900**	**280,900**	**280,900**
Biosolids Disposal			
Total disposal costs ($/yr)	**5,698,100**	**2,995,300**	**2,685,000**
Net O&M Costs			
Net costs ($/yr)[1]	**10,314,200**	**8,858,200**	**9,275,600**

[1] **Calculated relative to benchmark operation. Not to be used as absolute plant O&M costs.**

Source: Kennedy/Jenks Consultants

Figure 64 depicts the cost breakdown for each step of the process.

Figure 64: O&M Cost Breakdown for 100 MGD WWTP



Source: Kennedy/Jenks Consultants

Results from Figure 64 show that the differential increase in digester operating costs due to FW codigestion (compared to Scenario 1 benchmark) is insignificant compared to other O&M costs. Biosolids disposal costs still accounted for a significant portion of costs to the WWTP (at 29 to 55 percent of the overall operating costs), followed by gas cleaning costs (23 to 41 percent). The percentage and trends of these costs were similar to those previously observed for the 15 MGD. The cost of biosolids disposal steadily reduced with increasing FW addition. However, total O&M costs (Table 65) were highest for the sludge-only scenario ($10,300,200 per year), while 12.5 percent FW loading had the lowest O&M costs ($8,800,200 per year). It is important to note that these values are compared among themselves, as some costs were calculated relative to benchmark operation. Table 66 summarizes the revenue streams and energy savings potential for the different operating scenarios at the larger flowrates.

Table 66: Revenue and Energy Savings

	Scenario 1 (Sludge-only Digestion)	Scenario 2 (FW loading at 12.5% VS ratio)	Scenario 3 (FW loading at 25% VS ratio)
Tipping Fee Revenue			
Total FW received (TPD)	—	57.2	114
Total revenue from receiving FW ($/yr)	—	**625,900**	**1,251,700**
Energy Recovery			
Total energy produced (kWh/d)	113,300	165,500	192,000
Total energy savings ($/yr)	**5,787,800**	**8,458,000**	**9,810,500**

Source: Kennedy/Jenks Consultants

At a FW receival rate of 114 T/day, Scenario 3 (25 percent FW loading) offers the highest revenue potential from tipping fees. At the base-case rate of $30/T, Scenario 2 can obtain $625,900 of revenue per year, while Scenario 3 can obtain $1,251,700 per year. This revenue stream does not apply to the sludge-only scenario. Based on the biogas production potential of each operating condition, the total energy recovery savings were calculated to be $5,787,800, $8,458,000, and $9,810,500 for scenarios 1, 2, and 3, respectively.

7.5.1.3 Net Costs and Savings for Codigestion

The overall capital and O&M costs, energy savings, and tipping fee revenues were combined to determine the net spending for large-scale WWTPs. The payback period for implementing the FW codigestion and biogas recovery program was calculated based on the savings generated by the proposed processing method. This value was derived based on a comparison to the base-case operating scenario of digesting only sludge. These results are listed in Table 67.

Table 67: Net Spending and Payback Period for 100 MGD Plant

	Scenario 1 Sludge-only Digestion	Scenario 2 FW Loading at 12.5% VS Ratio	Scenario 3 FW Loading at 25% VS Ratio
Net Savings or Expenses			
Total annualized capital costs	1,016,400	1,568,700	1,841,700
Total O&M costs	10,314,200	10,269,900	10,523,500
Total savings from energy recovery	5,787,800	8,858,000	9,275,500
Total revenue from tipping fees	—	625,900	1,251,700
Net savings (expenses)	**(5,542,800)**	**(1,343,100)**	**(55,000)**
Savings compared to sludge-only digestion	—	**4,199,700**	**5,487,800**
Payback Period			
Total capital investment	14,315,500	22,094,800	25,939,500
Payback period	—	**5.3**	**4.7**

Source: Kennedy/Jenks Consultants

As stated in Section 7.3.3, the net savings (or expenses) for each scenario were not used as absolute saving/expenses to the WWTP, but as a comparison for FW codigestion to the benchmark. In this case, operating the larger-scale (100 MGD) WWTP with FW codigestion, alongside the biogas recovery system, was estimated to result in annual savings of $4,199,700 (Scenario 2) and $5,487,800 (Scenario 3) compared to the digester being operated without any FW (Scenario 1). These savings result in a payback period of approximately 5.3 years or 4.7 years for scenarios 2 and 3, respectively. Therefore, even though 12.5 percent FW loading had the lower O&M costs, it is still more beneficial for WWTPs to implement the FW codigestion program at the higher 25 percent VS loading. These calculations were made based on the base-case electricity price of $0.14/kWh and tipping fees of $30/T.

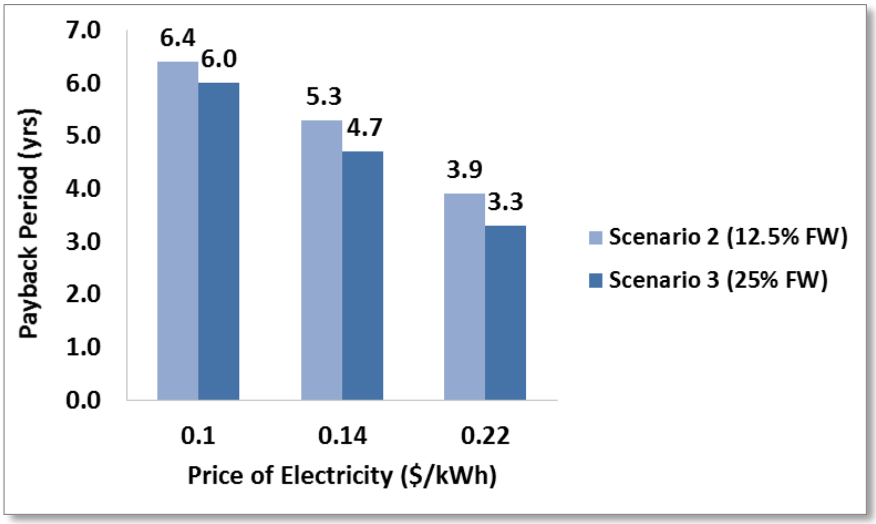
7.5.2 Codigestion Sensitivity Analysis

Sensitivity analyses were performed for the two savings- or revenue-generating variables: the price of electricity and the tipping fee. An analysis was also performed on the changing cost of biosolids disposal for the produced digester cake. A single input parameter was varied while keeping all other inputs at the base-case values discussed earlier. The following two subsections discuss how each variable affected the expected payback period for the codigestion projects.

7.5.2.1 Changes in Unit Electricity Price

The base-case electricity price used in the economic analysis was $0.14/kWh. Figure 65 shows how the expected payback period for the 100 MGD plant’s codigestion program (scenarios 2 and 3) changed as unit electricity price decreased to $0.10/kWh or increased to $0.22/kWh.

Figure 65: Electricity Price Sensitivity Analysis



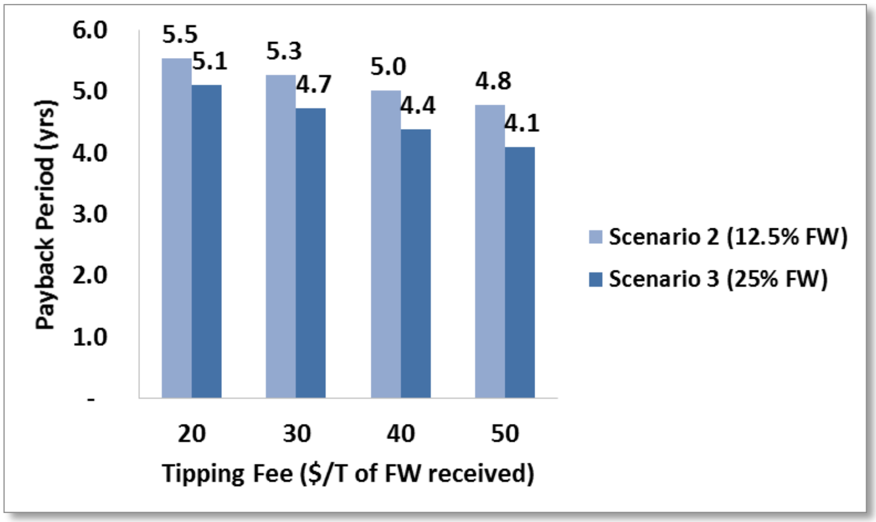
Source: Kennedy/Jenks Consultants

At $0.10/kWh, Scenario 2 (12.5 percent FW VS loading) is predicted to achieve a payback period of about 6.4 years, while a higher loading of FW in Scenario 3 (25 percent FW VS loading) could achieve a payback period of about 6 years. At $0.22/kWh, Scenario 2 achieved an estimated payback period of about within four years for both scenarios. These values are consistently lower than those obtained for the 15 MGD plant. Therefore, the incentive to establish a codigestion program increases in locations with higher electricity prices and with higher FW loading, as well as larger plant capacity or flowrates.

7.5.2.2 Changes in Tipping Fee

The effect of tipping fee variation ($20 to $50/ton) on the expected payback period for the codigestion program is summarized in Figure 66.

Figure 66: Tipping Fee Sensitivity Analysis



Source: Kennedy/Jenks Consultants

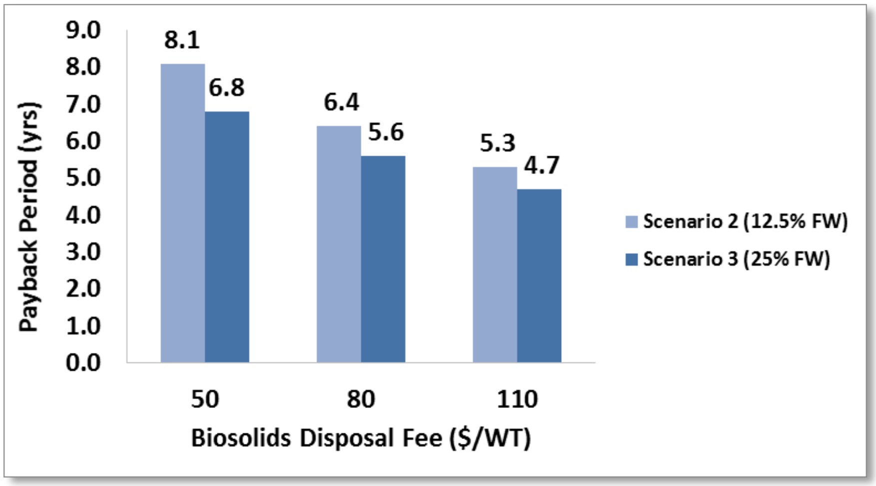
The base-case value for tipping fees was taken at $30/T, which resulted in a payback period of about 5.2 or 4.7 years (for scenarios 2 and 3, respectively). As the tipping fee decreased to

$20/T, the payback period was estimated to be 5.5 or 5 years, while increasing tipping fees were predicted to reduce payback periods. At $50/T, a payback period of 4.8 years or 4 years was predicted for FW loadings of scenarios 2 and 3, respectively. Based on these results, it can be concluded that at higher WWTP capacities, variation in tipping fees is a less significant factor in overall project feasibility.

7.5.2.3 Changes in Biosolids Disposal Fees

The effect of changing biosolids disposal costs ($50 to $110/WT) on the payback period for a 100 MGD plant was evaluated and is summarized in Figure 67.

Figure 67: Biosolids Disposal Costs Sensitivity Analysis



Source: Kennedy/Jenks Consultants

The base-case value for biosolids disposal fees was taken at $110/T, which resulted in a payback period of about 5.5 or 5 years (for scenarios 2 and 3, respectively). At lower disposal fees, the expected annual savings compared to sludge-only digestion are predicted to decrease, therefore, increasing estimated payback periods. As the disposal fee decreased to $80/T, the payback period for a 100 MGD plant was estimated to be 6.4 or 5.6 years. A further drop in disposal fees resulted in a predicted payback period of approximately eight or seven years for scenarios 2 and 3, respectively.

7.6 Benefits to California Ratepayers

In California, there are currently 268 WWTPs with more than 1 MGD of wastewater treatment capacity. The combined treatment capacity of these 268 plants is estimated to be approximately 3,000 MGD.

7.6.1 Enhanced Energy Recovery

The estimated energy generation potential through the digestion of all the wastewater sludge from these plants is about 125 megawatts (MW). Based on the results obtained in this study, the proposed project can increase digester gas production by approximately 46 percent to 70 percent, depending on the FW to sludge loading. This increased biogas production can yield an additional 58 to 87 MW of recoverable energy. Current estimated bioenergy production from WWTPs in California is 35 MW, from fewer than 25 plants. Based on this, a modest 30 percent market penetration is assumed for early adopting plants that have energy recovering capabilities. The proposed approach can enhance bioenergy production by 26 MW for these plants (approximately 70 wastewater treatment facilities). However, due to the cost-effective nature of the project, it is possible to anticipate a higher market penetration in the long run.

7.6.2 Reliability of a Renewable Resource

The proposed method for FW preprocessing and codigestion involves an alternative energy (bioenergy) production in a cost-effective manner for WWTPs. While there are some seasonal variations (organic content) in wastewater, such variations are much smaller than those with other forms of alternate energies, such as solar and wind. Further, it is reasonably fair to anticipate the overall supply of FW from collected MSW will be stable. Assuming the project is replicated at 30 percent market penetration, the diversion of FW from landfills to anaerobic digesters can sustainably produce approximately 60 MW of renewable energy. Since the proposed method is estimated to increase energy supply and reduce operating costs for WWTPs, rate payers should not be affected by the project costs.

7.6.3 Lower Carbon Footprint

Based on study results, the implementation of the proposed innovations has the potential to lower the mass of dewatered cake by 45 percent to 53 percent. The reduced volume of biosolids requiring disposal will lower the emissions from trucks used for hauling sludge to the disposal facility or landfill. Such reduction is estimated to lower the amount of dewatered sludge requiring disposal by up to 800,000 wet tons per year in California. At the conservative assumption of 30 percent market penetration, this could still result in a 245,000 wet tons per year reduction in sludge hauling.

7.6.4 Reduction in Greenhouse Gas Emissions

The proposed study facilitates the use of FW for biogas energy production rather than disposing of FW in landfills. On average, the estimated volume of FW production is approximately 0.25 lb/person/day (Skaggs, Coleman, et al. 2018) . Accordingly, California, with a population of 37 million, produces an estimated volume of 4,100 tons per day of FW. Assuming that the proposed study achieves a 30 percent market penetration, it would eliminate greenhouse gas emissions from approximately 370,000 tons of FW annually. This is calculated based on the codigestion performance observed at 25 percent FW VS loading.

7.6.5 Reduced Operating Costs

The economic analyses performed in this study showed that preprocessing at waste processing facilities using the proposed OREX method can reduce the cost of FW extraction by an estimated $65/T of MSW, compared to source-separating operations. Based on this estimate, the diversion of 370,000 tons of FW could result in savings of $69 million in preprocessing costs in California. In addition, WWTPs can benefit from savings in their overall O&M costs when implementing FW codigestion instead of sludge-only digestion. These savings vary based on plant size but can range between $100/T to $200/T of FW treated. For a potential diversion rate of 370,000 tons of FW per year, this can result in $37 million to $74 million of savings for state-wide WWTP annual expenses. Table 68 summarizes the overall project benefits to California.

Table 68: Statewide Benefits to California From Proposed FW Pre-Processing and Codigestion Method

Description	Benefit
Renewable Energy Production	Estimated increase of up to 87 MW (26 MW at 30% market penetration) of additional energy from WWTP digesters in California.
Biosolids Requiring Disposal	Estimated reduction of up to 800,000 WT/year (370,000 WT/year at 30% market penetration) from California WWTPs.
Greenhouse Gas Emission[1]	Estimated reduction of greenhouse emission by 201,000 $MTCO_2e$/year, due to 370,000 tons of FW diverted from landfills (30% market penetration).
Cost	46% reduction in FW preprocessing at waste processing facilities, compared to source-separating operations. Additional savings to WWTPs' operating expenses due to FW codigestion varies with plant size.

[1]Based on EPA's Waste Reduction Model (WARM)

Source: Kennedy/Jenks Consultants

7.7 Summary and Conclusions

The economic feasibility of the novel FW preprocessing and codigestion method were tested. The per ton cost estimates for preprocessing MSW by OREX at waste processing facilities is comparable to the base-case treatment of direct landfill disposal (under Bay Area estimates), under the assumptions used. Both of these methods were evaluated to cost $75/ton of MSW treated. This was significantly lower than the other preprocessing alternative, which required an expensive source-separating operation ($140/ton of MSW). This reduction in preprocessing costs for FW extraction translated to an estimated $15 to $30 million of savings for waste processing facilities across California. Sensitivity analyses on the landfill tipping fees indicated that, when compared to direct disposal costs, OREX preprocessing was a competitive option only if landfill tipping fees were greater than $75/T.

At WWTPs, the economic feasibility of codigestion with FW was evaluated for 15 and 100 MGD WWTPs. FW loadings of 12.5 percent and 25 percent of sludge VS were used in these evaluations. These capital costs ranged from $4.65 to $25.9 million. The largest capital expenditure was primarily due to implementing energy recovery units, such as gas cleaning and internal combustion systems. The annual O&M costs ranged between $1.40 to $1.59 million for the 15 MGD case and $8.85 to $10.3 million for the 100 MGD case. Approximately 25 to 50 percent of these operating costs were due to hauling and disposal costs of the produced digester cake, and another 20 to 40 percent due to biogas cleaning costs. In the case of smaller plants (15 MGD), the annual savings due to enhanced energy recovery ranged from $1.27 to $1.47 million for 12.5 percent and 25 percent FW loadings, respectively. For the 100 MGD case, this value varied between $8.86 to $9.28 million worth of energy savings. The additional revenue stream from FW receiving also introduced $94,000 to $188,000 for the 15 MGD plant, and $0.63 to $1.25 million for the 100 MGD plant. The expected annual savings from FW codigestion and energy recovery resulted in a payback period of approximately 7.8 or 6 years on initial investments for the 15 MGD plants (for 12.5 percent and 25 percent FW loadings, respectively). Based on the economic analysis for the 100 MGD plant, the payback period was estimated to be within approximately five years for the base-case costs. However, these values were tested against varying electricity prices, tipping fees, and biosolid disposal costs. Results indicated that the relative savings (and payback period) for incorporating FW codigestion and biogas recovery at both the 15 MGD and 100 MGD plant can vary greatly with changes in these variables, particularly biosolid disposal costs. Also, the economic analyses in this section assumed a new installation for the necessary FW receiving station and upgrades of biogas processing facilities. However, the economic analysis discussed here will be different for plants that have existing infrastructure.

CHAPTER 8:
Measurement and Verification by Base Energy

This chapter describes the findings of the measurement and verification (M&V) of energy production and consumption associated with the codigestion activities at SVCW. The purpose of this chapter is to outline the inputs and results. Detailed information can be obtained from the M&V report attached in Appendix A.

Kennedy/Jenks Consultants contracted with BASE Energy, Inc. to provide third party M&V of the potential effects on electrical energy consumption and biogas production due to codigestion of FW pre-processed with OEP system at Recology and the on-site OPS units. To this effect, Base developed a detailed M&V plan to determine the power and energy consumption of the systems and the biogas production for each test condition.

The specific goals of the M&V plan were to determine:

- The energy consumption of key components including OEP and OPS, pumps, digester mixing units, and dewatering units
- The energy production (biogas production) of the test digester
- The effects of FOG and FW on energy consumption and energy production of the entire system

8.1 Measurement Inputs

8.1.1 Equipment Considered

Table 68 lists all the equipment considered for the M&V analysis.

Table 69: M&V Parameters

Equipment	Rating	Parameter Measured	Source	Provided By	Resolution
Digester Equipment					
Digester #2	—	Total sludge flow, gal/day	SCADA	KJ	Daily
	—	Total FOG flow, gal/day	SCADA	KJ	Daily
	—	Total food waste flow, gal/day	SCADA	KJ	Daily
	—	Biogas production	SCADA	KJ	Daily
Sludge Mixing Pump*	60 hp	Power	Spot Power Measurement	BASE	Instantaneous
Sludge Recirculation Pump*	20 hp	Power	Spot Power Measurement	BASE	Instantaneous
Heat Exchanger Equipment					
Hot Water Recirculation Pump*	7.5 hp	Power	Spot Power Measurement	BASE	Instantaneous
Primary Recirculation Pump*	15 hp	Power	Spot Power Measurement	BASE	Instantaneous
Secondary Recirculation Pump*	7.5 hp	Power	Spot Power Measurement	BASE	Instantaneous
Dewatering Equipment					
Rotary Presses	(2) 20 hp	Current	Indirect Measurement	KJ	Daily
Feed Pumps	(2) 10 hp	Current	Indirect Measurement	KJ	Daily
FOG Handling Equipment					
Chopper Pumps	(2) 10 hp	Current	SCADA	KJ	Daily
"Beast" Drum Screen	(2) 2 hp	Current	SCADA	KJ	Daily
Transfer Pumps	(2) 10 hp	Current	SCADA	KJ	Daily
Food Waste Handling Equipment					
Mixer	17 hp	Current	Data Logger	KJ	Daily

Equipment	Rating	Parameter Measured	Source	Provided By	Resolution
Transfer Pump	10 hp	Current	Data Logger	KJ	Daily
Feed Pump	3 hp	Current	Data Logger	KJ	Daily
Paddle Finisher	30 hp	Current	Data Logger	KJ	Daily
Organic Extrusion Press					
Organic Extrusion Press (OEP)	235 kW	Current	Data Logger	BASE	1 minute
Intake Conveyors	7.5 kW	Current	Data Logger	BASE	1 minute
Discharge Conveyors	0.37 kW	Current	Data Logger	BASE	1 minute
Discharge Conveyor	7.5 hp	Current	Data Logger	BASE	1 minute
Discharge Conveyor	5 hp	Current	Data Logger	BASE	1 minute

*** indicates continuous operation.**

Source: Kennedy/Jenks Consultants

The table shows that the source of energy data is either from spot measurements (where applicable, if equipment operations do not change), SCADA where such data was continuously recorded, data loggers for FOG handling, FW preprocessing (OREX), and FW polishing. Power consumption of all equipment associated with the Digester #2 system was taken into consideration. For the benchmarking tests, the TPS and TWAS sludge pump power consumption was considered. In FOG tests, the energy consumption of the feed sludge pumps as well as the FOG Beast system was accounted for. For the FW tests, the FW preprocessing OREX system as well as the on-site OPS polishing system was considered. Similar to the previous tests, the TPS and TWAS sludge pumps were also considered. For all the tests, the energy associated with test digester equipment was considered. All of the digester equipment listed operates at constant speed 24/7 and therefore the related energy use is not influenced by digester loading—that is, it does not vary with each test.

Dewatering operations energy was also considered for each test but it was not a direct measurement. An indirect energy derivation for dewatering equipment was used for each test. As discussed in chapters 3 and 5, typical plant operation has all sludge from Digester #2 going to Digester #3. The sludge from Digester 3 then feeds the dewatering system. Due to this dewatering operation, energy use for dewatering Digester 2 sludge cannot be measured directly. In addition, operation of the dewatering system has day-to-day deviations due to different plant operational aspects, not necessarily related to this project’s codigestion test. For these reasons, a broad metric of the kWh/dry ton collected over time was used to derive the dewatering energy demand. This metric is based on KWh power data collected by facility over a period of six months. Digester 2 dry tons dewatered for each test period was calculated based on the percent solids of sludge leaving Digester 2. Therefore, the energy use associated with dewatering was prorated. The average energy use of the dewatering system was calculated using an energy intensity metric of 47 kWh per dry ton dewatered.

8.1.2 Test Conditions

The energy consumed with the benchmarking (sludge), FOG, and FW tests discussed in chapters 4, 5, and 6 respectively was estimated. Table 68 summarizes the test conditions.

Table 70: Summary of Test Conditions

Test	Average Sludge Flow (GPD)	Average FOG Flow (GPD)	Average Food Waste Flow (TPD)	Average Dry Tons to Dewatering (DT/day)	Average Methane Flow (cu.ft./day)
Sludge Test 1	40,390	0	0	3.6	83,935
Sludge Test 2	70,921	0	0	6.7	105,712
FOG Test 1	45,685	8,250	0	4.3	98,419
FOG Test 2	57,525	12,862	0	5.2	133,535
FOG Test 3	41,548	27,175	0	4.8	177,876
FW Test 1	29,894	0	4.24	2.23	76,787

Source: Kennedy/Jenks Consultants

Table 69 summarizes the inputs for the various equipment discussed in the previous section. Results from the benchmarking tests, FOG tests, and FW tests (chapters 4, 5, and 6) respectively were used to develop all the inputs for this M&V. Sludge, FW, and FOG are fed to the digester, the generated biogas is cleaned and used for energy cogeneration, and downstream biosolids are dewatered and disposed of. This energy generated and the energy consumed for all the equipment in the codigestion process is calculated.

Base Energy performed the following calculations to estimate the energy consumed and generated for each test:

- The average daily energy consumption of the targeted equipment for each test condition
- The average daily methane gas production for each test condition, based on daily biogas production and percent methane gas of the gas
- The methane gas production electrical energy intensity for each test condition based on the daily methane gas production and daily electrical energy consumption of the system
- The ratio of energy produced, in the form of methane gas, to total associated energy consumed by the system for each test condition

Other details of the calculations are given in Appendix A.

8.2 Summary of Results

Individual results of each test are presented in Appendix A. Table 70 is a combined table showing all the results.

Table 71: Comparison of Energy Consumption of Test Periods

Test	Average Methane (cu.ft./day)	Total Average Energy Use (kWh/day)	Methane Production Normalized for Total Energy Use (CF/kWh)	kWh Consumed Normalized for Methane Production (kWh/CF)	Ratio of Energy Produced to Energy Consumed
Sludge Test 1	83,935	1,639	51.2	0.020	9.01
Sludge Test 2	105,712	1,639	64.5	0.016	11.4
FOG Test 1	98,419	2,081	47.3	0.021	8.3
FOG Test 2	133,535	2,161	61.8	0.016	10.8
FOG Test 3	**177,876**	**2,651**	**67.1**	**0.015**	**11.8**
FW Test 1	78,997	2,660	29.7	0.034	5.33
FW Test 2	81,207	2,679	30.3	0.033	5.22

Source: Kennedy/Jenks Consultants

Of all test conditions, FOG Test 3 had the highest methane production per kWh consumed. Overall, this test had the lowest energy consumption per cu.ft. of methane gas produced. FOG Test 3 also had the highest ratio of energy produced to energy consumed of any of the test conditions. This test also had the highest ratio of volume of FOG to volume of sludge of any of the FOG test. Comparing FOG Test 3 to FOG Test 2, FOG Test 3 had a slightly lower total volume fed (sludge plus FOG). The higher ratio of energy produced to energy consumed of FOG Test 3 aligns with the codigestion effects discussed in Chapter 5, where the highest gas production was observed from this test. FOG Test 2 had a higher ratio of volume of FOG to volume of sludge and higher total volume fed than FOG Test 1, which may be the reason for a higher ratio of energy produced to energy consumed. Sludge Test 2 (Benchmarking Test 2) had higher overall methane production than Sludge Test 1 but had lower methane production when normalized for total sludge flow. Sludge Test 2 had a higher methane production when normalized for total energy consumption and thus a higher ratio of energy produced to energy consumed.

The FW tests had the least ratio of energy produced to that consumed over all the tests. The main contributing factor to this low energy efficiency is the high energy consumption of the OREX press. Another contributing factor is likely the relatively low total digester loading, compared to all other tests. FW Test 1 had a higher ratio of volume of food waste to volume of sludge and a higher total volume fed (sludge plus food waste) than FW Test 2. FW Test 1 would therefore be expected to have a higher ratio of energy produced to energy consumed as a result, which is not shown to be the case. Although FW Test 2, had a lower ratio of energy produced to energy consumed, it had a higher average methane gas production. This is due to the higher solids percent in FW, so the VS loading was more in FW Test 2, while the volume of FW fed was less in FW Test 2.

CHAPTER 9:
Production Readiness Plan

The project demonstrated two novel, complementary approaches to lower the cost of organic (food) waste codigestion: 1) a new technology to lower the preprocessing cost of food waste, and 2) a new strategy to lower the mass of dewatered cake solids requiring disposal during the codigestion process.

The proposed food waste preprocessing includes two process steps, an organic extrusion press (OREX) for extrusion of organic materials and removal of large inorganic materials, and a polishing system for removal of finer inorganic and inert materials from the OREX extract. Both the OREX and the polishing technologies used in this study have reached commercialization stage. A full-scale OREX unit installed at the San Francisco Recology facility was used for food waste extraction for this project. The technology has been successfully implemented in multiple WWTPs throughout Europe, ranging in size from 20,000 to 100,000 tpy. Anaergia is currently developing several projects in North America. The key components of the OREX extracted food waste polishing system, including the Anaergia mixer and a paddle finisher, have also been commercialized and used in full-scale wastewater treatment plants. Hence, these technologies can be readily installed and operated with minimal modifications for any site-specific requirements. The costs indicated in the economic evaluations section (Chapter 7) are a fair representation of the equipment costs.

A second approach used in this study to lower the cost of food waste codigestion is the strategic addition of food waste to allow for synergistic interaction of food waste and sludge solids that will improve dewatering and lower the mass of cake solids requiring disposal. This approach can be readily adopted to dewatering in wastewater treatment facilities with some bench scale dewatering evaluation that may be required to optimize the loading ratio.

CHAPTER 10:
Summary and Conclusions

This project successfully demonstrated a novel FW preprocessing system and a new strategy to lower the mass of dewatered cake solids from codigestion. The following specific project objectives were accomplished:

1. Reduction in FW preprocessing costs (approximately 54 percent) using the novel preprocessing and polishing method prior to codigestion compared to source separation and polishing of food waste currently practiced in many facilities
2. Increase in gas production with strategic addition of FOG and FW for codigestion (approximately 3 percent to 58 percent), in comparison to the benchmarking tests
3. Increase in dewatered cake percent solids leading to a decrease in mass of cake hauled and requiring disposal (3.2 percent to 17.7 percent) through codigestion of FOG and FW from the plant
4. Estimated return on investment of five to eight years for WWTPs implementing food waste codigestion under the conditions assumed.

10.1 Key Conclusions

This section details results of the main objectives.

1. OREX preprocessing of the commingled waste reduced source separation costs by almost half.
    a. The total cost to waste processing facilities for extracting FW from MSW was \$75/T for OREX preprocessing compared to approximately \$140/T for preprocessing through the source separation and subsequent polishing currently practiced by many waste processing facilities. The cost of OREX preprocessing is comparable to disposal of commingled waste in landfills (\$75/T), under the assumptions used in this study. However, preprocessing of food waste by the proposed technology (followed by codigestion) provides the additional benefit of diversion of organic material from landfills. This indicated that OREX preprocessing was more cost efficient for this project.
2. Codigestion with targeted strategic loadings of FOG and FW improved total gas production, VSR, and unit gas production.
    a. FOG Codigestion: Addition of FOG increased gas production per pound of VS as well as the percent of VS destroyed. For the highest amount of FOG added (48 percent of sludge VS), the gas production per pound of VS destroyed increased by 52 percent, and the VS destruction increased by 4.3 percent. Overall, per pound of combined sludge and FOG added, the gas production increased by 67 percent compared to a pound of only sludge fed to the digester.
    b. FW Codigestion: Addition of FW increased gas production per pound of VS as well as the percent of VS destroyed. For the highest amount of food waste added (25 percent of sludge VS), the gas production per pound of VS destroyed

    increased by 14 percent, and the VS destruction increased by 11.5 percent. Overall, per pound of combined sludge and food waste added, the gas production increased by 20 percent compared to a pound of only sludge fed to the digester.

3. Codigestion with targeted strategic loadings of FOG and FW increased the dewatered cake solids percent, leading to a decrease in cake mass hauled from the plant.
    a. Dewatering of FOG Codigested Sludge: In general, addition of FOG improved dewatering of the codigested sludge. Addition of FOG at 12.5 percent of sludge VS increased the percent solids in the dewatered cake by 21.4 percent (compared to an average percent solids of the benchmarking tests), a net reduction of 17.7 percent in the cake requiring disposal. Codigestion tests performed through addition of 26 percent and 48 percent of sludge VS did not appreciably improve dewatering. However, these two tests were performed at lower than typical acclimation time due to constraints with FOG inventory. It is not clear if lack of sufficient acclimation time resulted in the dewatering results observed with these two tests.
    b. Dewatering of Food Waste Codigested Sludge: Addition of FW improved the dewatering efficiency of the codigested sludge. On average, the percent solids of the dewatered cake increased by approximately 13 percent (compared to an average percent solids of the benchmarking tests), a net reduction of 11.5 percent in the cake requiring disposal, compared to dewatering of sludge digested without any FW addition.
4. Implementation of codigestion can yield economic benefits to WWTPs
    a. Preliminary economic evaluations indicated that implementation of codigestion can be cost effective for WWTPs. Results indicated that the return on investment for implementation of codigestion can vary from 6 to 8 years, for a 15 MGD plant, and 5.3 to 4.7 years for a 100 MGD plant, under the assumptions used in this report. The major expenses include construction of a receiving station and food waste polishing unit and installation of gas cleaning and energy generation equipment. The major revenue (or cost savings) sources include tipping fee, increased gas production, and reduction in sludge hauling cost.

10.2 Additional Conclusions

The codigestion study offers other important findings.

1. Biogas Quality: In general, the biogas quality did not change significantly due to codigestion. The methane content in the biogas varied from 59 percent to 63 percent in all the tests, except in one test using FOG, in which the methane content was 70 percent. The CO_2 content varied from 35 percent to 40 percent in all the tests, except in the previously referenced test using FOG, in which the CO_2 content was 33 percent. H_2S levels were generally below 200 ppmV, except in one benchmarking test (580 ppmV) and a test using FOG (1629 ppmV). However, the higher levels of H_2S in these tests appeared to coincide with problems in ferric chloride dosing.
2. Polymer Demand for Dewatering: In general, polymer demand for dewatering appeared to increase during codigestion. In the two benchmarking tests, polymer demand was 28

and 35 lb/dry ton. The polymer demand in FOG or food waste codigested sludge varied from 28 to 34 lb/DT.

3. Dewatered Cake Odor: Total volatile organic sulfur compounds (TVOSCs, consisting of methyl mercaptan and dimethyl sulfide) emissions from dewatered cake were measured to evaluate the effect of codigestion on cake odor. In general, addition of FOG or food waste appear to increase the dewatered cake odor. The peak TVOSC levels in the two benchmarking tests were similar: approximately 130 ppmV. In the FOG codigestion studies, the peak TVOSC level increased to 550 at a lower addition of FOG VS (26 percent of sludge VS), but decreased to 180 ppmV, when FOG loading was increased to 48 percent of sludge VS. The peak TVOSC levels in the dewatered cake during the FW codigestion tests were 210 and 300 ppmV. In past studies, addition of food waste at approximately 25 percent of sludge VS increased TVOSC levels but decreased the TVOSC levels below that produced from dewatered cake from sludge-only digestion systems.
4. Energy Production to Energy Consumption Ratio: In the independent M&V studies performed by BASE Energy, Inc, the energy production to energy consumption ratios for the benchmarking tests were 9 and 11.4. For the FOG tests, these ratios were 8.3 to 11.8, a 42 percent increase in the test using the highest amount of FOG added. In the FW tests, these ratios were 5.3 and 5.2 for the two tests respectively. These ratios are due to the operation of the OREX unit, which is an anticipated energy-consuming component. Although the ratio of the energy production to energy consumption is low for FW, the net amount of additional energy produced is significantly higher for a similar or lower total volume of only sludge fed during codigestion, resulting in significant energy and economic benefits.

10.3 Conclusions From the Economic Analysis

Based on all the assumptions and results considered in Chapter 7, main results of economic analyses include the following.

- Preliminary estimates for the capital investment for 12.5 percent and 25 percent FW loads for a 15 MGD and 100 MGD plant ranged from $4.7 to $26 million. The largest capital expenditure was primarily due to implementing energy recovery units, such as gas cleaning and internal combustion systems.
- The difference in the annual O&M costs between the sludge-only digestion and the 12.5 percent FW VS and 25 percent FW VS scenarios ranged between a decrease of $183,500/yr and $118,400/yr respectively for the 15 MGD case. For 100 MGD, the codigestion costs decreased by $1,456,000/yr and $1,038,650/yr for the two FW scenarios respectively.
- In the case of the 15 MGD plant, the annual savings due to enhanced energy recovery ranged from $1.3 to $1.5 million for 12.5 percent and 25 percent FW loadings, respectively. For the 100 MGD case, this value varied between $8.9 to $9.3 million. This was estimated at an electricity cost of $0.14/kWh.
- The additional revenue stream from FW receiving as tipping fees also introduced $94,000 to $188,000 for the 15 MGD plant and $0.63 to $1.25 million for the 100 MGD plant. The tipping fee was assumed to be $30/T.

- Assuming base costs for tipping fees of 30$/T, electricity cost at $0.14 /kWh, and hauling costs of $110/T, the payback period was calculated to be eight and six years for the two increasing FW loadings for the 15 MGD plant respectively. For the same base costs, in a 100 MGD plant, the payback periods were 5.3 years and 4.7 years, respectively.
- To determine the effects of the variable unit costs affecting economics of codigestion in various areas, sensitivity analyses were conducted by varying the unit cost of electricity, tipping fees, and biosolids hauling and disposal costs.
    - For 15 MGD, decreasing electricity price to $0.10/kWh, 12.5 percent FW VS loading increased the payback period to 10 years, while the 25 percent FW VS loading could achieve a payback period of about 7.5 years. Increasing the cost to $0.22/kWh, 12.5 percent FW VS achieved an estimated payback period of about 6 years and 25 percent FW VS resulted in payback within 4.5 years. These payback periods decreased to less than four years for the 100 MGD plant.
    - Increasing tipping fees to $50/T decreased the payback periods to seven and five years respectively for the two increasing FW loadings in the 15 MGD plant. A decrease to $20/T only raised the payback period slightly. For the 100 MGD plant, as the tipping fee decreased to $20/T, the payback period was estimated to be 5.5 or 5 years. At $50/T, a payback period of 4.8 years or 4 years was estimated.
    - For a 15 MGD plant, as the disposal fee decreased to $80/T, the payback period was estimated to be 10 or 7 years. A drop in disposal fees to $50/T resulted in a payback period of 12.5 or 8.5 years for the two loadings, respectively. As the disposal fee decreased to $80/T, the payback period for a 100 MGD plant was estimated to be 6.4 or 5.6 years. A further drop in disposal fees resulted in a payback period of eight or seven years.
  - These results indicated that the relative savings (and payback period) for incorporating FW codigestion and biogas recovery at both the 15 MGD and 100 MGD plant can vary greatly with changes in variables.

10.4 Statewide Benefits Conclusion Summary

California will benefit from enhanced energy recovery, reduced greenhouse gas emissions, a smaller carbon footprint, and reduced costs by adopting the new approaches proposed in this study that involve a readily-available alternative sustainable source.

The increased biogas production from the diversion of food waste from landfills to anaerobic digesters can sustainably produce an additional 26 MW of recoverable energy, if a 30 percent market penetration is considered. At the same conservative assumption of 30 percent market penetration, the reduced volume of biosolids resulting from food waste codigestion could result in a 245,000 wet tons per year reduction in sludge hauling.

Assuming a 25 percent food waste volatile solids codigestion, the proposed technology has the potential to eliminate greenhouse gas emissions from approximately 370,000 tons of food waste annually. Preprocessing this volume of food waste using the proposed OREX method can reduce the cost of food waste extraction by an estimated $28 million in preprocessing costs. By diverting some 370,000 tons of food waste annually, the proposed technology can also save wastewater treatment plants between $15 and $30 million in annual operational costs. Due to these savings, ratepayers should not be affected by the project costs.

LIST OF ACRONYMS

Term	Definition
AD	anaerobic digestion
CEC	California Energy Commission
COD	chemical oxygen demand
CST	capillary suction time
C/N	carbon: nitrogen (ratio)
DMS	di-methyl sulfide
DT/day	dry ton/day
EC	electrical conductivity
EPS	extracellular polymeric substances
FA	free ammonia
FAN	free ammonia nitrogen
FOG	fats, oils, grease
FW	food waste
GC	gas chromatograph
GC - SCD	sulfur chemiluminescence detector for GC
GC - FID	flame ionization detector for GC
GC - TCD	thermal conductivity detector for GC
GHG	greenhouse gases
gpd	gallons per day
gpm	gallons per minute
HRT	hydraulic retention time
inch Hg	inches of mercury, a unit of measurement for pressure
lbs VS/cu.ft./day	pounds VS/ cubic feet/day
M/D	monovalent to divalent (cation ratio)
mg/L	milligram per liter
MGD	million gallons per day
mS/cm	millisiemens per centimeter
MS-OFMSW	mechanically sorted OFMSW
MSW	municipal solid waste
MT	methyl mercaptans
MW	megawatt

Term	Definition
O&M	operations and maintenance
OFMSW	organic fraction of municipal solid waste
OEP/OREX	organic extrusion press
OPS	organic polishing system
ppm	parts per million
ppmV	part per million by volume
Psi	pounds per square inch
s	seconds
SCADA	supervisory control and data acquisition
SM	standard methods
SC-OFMSW	separately collected OFMSW
SS-OFMSW	source separated OFMSW
SVCW	Silicon Valley Clean Water
TNT	Test `N Tube™
TPD	tons per day
TPS	thickened primary sludge
tpy	tons per year
TSS	total suspended solids
TVOSC	total volatile organic sulfur compound
TWAS	thickened waste activated sludge
US EPA	United States Environmental Protection Agency
VFA/VA	volatile fatty acids/volatile acids
VSF	volatile solids fraction
VSR	volatile solids reduction
WARM	waste reduction (model)
WAS	waste activated sludge
WE&RF	Water Environment & Reuse Foundation
WERF	Water Environment Research Foundation
WTE	waste to energy (model)
W/W	weight/weight
WWTP	wastewater treatment plant

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APPENDICES

The following appendices are available under separate cover (Publication Number CEC-500-2020-069-APA-B) upon request by contacting Abolghasem Edalati at: Abolghasem.Edalati-Sarayani@energy.ca.gov.

- Appendix A: Measurement and Evaluation Report by Base Energy
- Appendix B: Conference Presentations and Abstracts