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Energy Research and Development Division

FINAL PROJECT REPORT

Optimizing Food Waste Anaerobic Digestion at Water Resource Recovery Facilities

Skid-Mounted Mobile Pilot/Education Units for Source-Separated Organics/Biosolids Processing with Cogeneration Capabilities

Gavin Newsom, Governor
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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.

Optimizing Food Waste Anaerobic Digestion at Water Resource Recovery Facilities is the final report for the Skid-Mounted Mobile Pilot/Education Units for Source-Separated Organics/Biosolids Processing with Cogeneration Capabilities project (Contract Number: EPC-17-022) conducted by Lystek International Ltd. The information from this project contributes to the 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 ERDD@energy.ca.gov.

ABSTRACT

This project integrated a small-scale skid-mounted system with a food waste de-packaging unit (separation of food waste from non-organic materials) with anaerobic digestion and thermal hydrolysis capabilities to efficiently process food waste and support California's efforts in diverting organic waste from landfills. Food waste digestion or co-digestion at wastewater treatment facilities leverages existing infrastructure and onsite expertise, reduces greenhouse gas emissions, and enhances production of biogas, which is a renewable energy source.

The complete system, installed at the Goleta Sanitary District in Santa Barbara County, California, included a containerized de-packaging unit; two 2,000-gallon anaerobic digesters; flare, feed, and discharge equipment; and a full system for process control and data collection. The system pre-processed food waste from dining halls at the University of California, Santa Barbara into an organic slurry in the de-packaging system before pumping to the anaerobic digesters.

The project team investigated the effects on anaerobic digestion from pre-treating the organic slurry using Lystek thermal hydrolysis, which increased biogas yields from difficult-to-digest food wastes. After initial acclimation, digester gas production was 21% higher with the thermal hydrolysis product than from untreated organic slurry.

Keywords: Anaerobic digestion, thermal hydrolysis process, organics preprocessing, food waste, gas production

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TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

The State of California is striving to achieve a greater diversion of waste, specifically organic waste, from traditional disposal (such as landfills) and toward alternative uses. The primary goal of this diversion is to reduce greenhouse gas (GHG) emissions from controllable sources. New regulations and rules have been passed to mandate the removal of organics (green waste, food waste, etc.) from landfills with the regulator's established goal of diverting up to 75% of existing organics (based on 2013 baseline data) from landfills by 2025. This would require the diversion of 5.5 million tons of organic waste from landfills, and an estimated 150 new processing and recycling sites would be needed to handle this quantity of material. The California Association of Sanitation Agencies (CASA) estimates that wastewater agencies could receive and process as much as 75 % of food waste, fats, oil, and grease currently landfilled in California using anaerobic digestion (AD) in existing digester systems. The primary output of processing organic material at wastewater treatment plants (WWTPs) is increased generation of renewable methane, and the resulting ability to generate renewable electricity or other energy fuel products. On a state-wide basis, this renewable resource represents the potential to generate a significant quantity of renewable electricity and thus reduce the need for the demand for fossil fuel exploration and demand.

The process and benefits of AD of organic wastes is well documented in research literature. However, in practice, WWTPs are often reluctant to receive such organic feedstocks due to concerns that receiving and processing organic materials may interfere with their regulatory and permit mandates and impede their ability to produce clean water.

Such concerns may be both operational and financial. Operationally, there is concern that contaminants (inorganic materials, such as animal bones that do not degrade, or household refuse, including plastics, metals and glass) may cause mechanical damage and reduce life-cycle time of equipment; reduce digester residence time decreasing processing efficiency; cause potentially toxic side effects that may upset the digesters' functional activity; increase the potential for plant odor discharges; require additional permits; and produce increased quantities of biosolids which requires further management. Financially, without a commensurate revenue stream, the likelihood of operating expense increases (due to increased maintenance activity and potentially additional labor requirements) is a disincentive to processing organic wastes.

Specifically, operator concerns regarding process upsets need to be addressed before organic waste can be feasibly diverted to WWTP for processing. In addition, demonstrating that there are potential financial benefits will help incentivize WWTP operators to accept organic wastes.

Project Purpose

The broad purpose of this project was to demonstrate the ability of a WWTP to receive organic wastes, process them through AD to produce biogas without upsetting the wastewater treatment process, and to document that the resulting biogas can be converted into electricity through co-generation. The demonstration scale project was conducted at an operational

WWTP to support the concept of full-size commercial deployment at existing WWTP plant operations, help shorten the time to market, and further the integration potential of solid waste companies working with WWTPs to co-process organic waste material.

By successfully demonstrating these capabilities, the project should increase confidence and incentivize WWTP operators to receive and process organic wastes, which will: increase the production of renewable energy in California, increase the diversion of organic wastes, and reduce GHG emissions.

To do so, the project was broken into a number of specific research goals and objectives, namely:

1. Produce a liquid slurry from source-separated organic (SSO) waste that is free of contaminants using a commercially available technology;
2. Process the slurry in anaerobic digesters to produce biogas, without the feedstock upsetting the AD process;
3. Calculate that on a weight per weight basis 30% more biogas is generated in food waste digestion compared to municipal sludge digestion;
4. Treat the organic slurry with a commercially available thermal hydrolysis technology and show greater biogas production relative to the untreated slurry; and
5. Conduct an economic analysis of the process to determine the benefits to the State and ratepayers.

The project team focused on food waste digestion because the economic incentives are currently larger, particularly the eligibility of food waste-only digestion for Renewable Identification Number (RIN) credits. A RIN credit is a credit that is generated each time a gallon of renewable fuel is produced and can be sold independently of the fuel produced.

Project Approach

The project was led by Lystek International Ltd. (Lystek), with support provided by the key stakeholders: Goleta Sanitary District (GSD), the University of California Santa Barbara (UCSB) Food Services group and Marborg Industries. Lystek is an environmental technology company providing technology to the municipal and industrial sectors to recover resources and utilize nutrients from waste streams. Lystek provided the technology used in this demonstration, and was responsible for operations, data collection and analysis. GSD is a special district on California’s south coast; its mission is to protect public health and the environment through responsible wastewater collection, treatment, and resource recovery to meet present and future community needs. GSD hosted the demonstration, provided operational support and laboratory services, as well as managed SSO receiving infrastructure and logistics. UCSB provided SSO from its campus dining halls over the course of the project. Marborg Industries is a local solid waste management company, who was responsible for transport of SSO from UCSB to GSD during the project.

The major barrier to starting the project was obtaining the necessary state, California Environmental Quality Act (CEQA), and local, Santa Barbara Air Pollution Control District (SPAPCD), environmental approvals and permits. Permits were obtained with the support of a specialized environmental consulting company, familiar with both the state and local processes.

The project was conducted over a 10-month period at an operating Water Resource Recovery Facility (WRRF), and designed to mimic the normal, daily operations of the site, but on a much smaller scale. The system was operated by experienced WRRF staff, and as would be expected, there were challenges encountered over the course of the project. Some were operational, which were resolved by adapting operating procedures and/or replacing equipment as needed. The biggest challenge, however, was running the project during the beginning of the COVID-19 pandemic. When the pandemic was declared, UCSB disbanded on-campus learning and closed its dining halls, which ceased delivery of SSO to the site. In collaboration with the hauler, GSD was able to source SSO from a local restaurant, but this source proved sub-optimal for long term use as a digester feedstock, leading to the end of the food waste digestion trial. The other critical challenge imposed by the pandemic was the severe restrictions on travel and site access by third-party technical and operational support personnel. This required that needed support could only be served through remote accessing and limited real-time and visual observance of operations equipment and instrumentation. This was mitigated by additional operating support from GSD, video communication tools and increased communication between Lystek and the project operators.

To assess the performance of the technology, relevant process data (such as digester feed and biogas flow rates) were collected automatically by specialized equipment installed in the system, and samples collected from the process were analyzed by accredited laboratories. The process data and sample data were compiled and analyzed by Lystek, with input by members of the Technical Advisory Committee (TAC) and Dr. George Nakhla of Western University.

The TAC was comprised of four members: Tej Gidda, Ph.D, GHD, Inc.; Mohammad Abu-Orf, Ph.D, VP, Hazen & Sawyer; Matt Fore, Santa Barbara County and UCSB; and, James Dunbar, Lystek. The TAC provided oversight of the project and helped determine solutions to any identified issues encountered during the project term. The TAC provided valuable technical comments for items that needed to be addressed, such as sampling and testing parameters, instrumentation selection, and data review and reporting format. The TAC served its role and stayed active during the major components of the project term.

Project Results

Results from the project demonstrated the successful diversion of organic wastes from landfill disposal for conversion to biogas through AD. The combination of increased biogas production and a potential revenue stream from organic waste tipping fees makes the proposed use of WWTPs to process food wastes a potentially feasible strategy for the State of California to pursue in its drive to reach its diversion goals. Major highlights, as well as lessons learned, are summarized below:

Food Waste Pre-Processing

The organic processing technology tested was able to produce a liquid slurry from the received SSO that contained < 0.1% contamination (non-food items) by wet weight, which was consistent with the manufacturer’s equipment specifications. In SSO pre-processing at a commercial scale, a complete system would provide grit removal and size reduction steps in the pre-processing operation. Grit removal and size reduction are required to produce an optimal digester feedstock. In this demonstration, the lack of grit removal and size reduction steps during SSO pre-processing contributed to unnecessary operational interruptions and increased operator intervention.

During the demonstration, organic processing operations were by far the most labor-intensive activity of the process. Large WWTPs may be able to benefit from their size and relative economies of scale and conduct pre-processing operations on site. Smaller WWTPs (unable to leverage any scale) may need to develop joint agreements with waste haulers to have feedstocks pre-processed off-site and then delivered in slurry form.

Anaerobic Digestion of Food Waste

AD of organic (food) waste only, (referred to as "mono-digestion") resulted in greater gas production than municipal sludge-only digestion at GSD, and co-digestion (simultaneous digestion of food waste and municipal sludge) reported elsewhere[1]. Per pound of dry mass fed to the digesters, biogas yields for food waste digestion were more than 30% higher than for municipal sludge digestion at GSD.

Methane content in the biogas ranged between 56% – 70%, averaging 62.2%. In a typical WWTP, the methane fraction of the biogas gas is at a similar average of 60%. Higher methane content in the biogas is beneficial as it will reduce downstream treatment requirements and costs associated with upgrading and purifying the biogas.

Hydrogen sulfide content (post-commissioning phase) in the biogas ranged from 10 parts per million (ppm) to 200 ppm. Although higher than the 50 – 65 ppm typically seen at WWTPs, it is easily managed by the common WWTP practice of injecting small volumes of iron-containing solutions (e.g. ferrous or ferric chloride) into the digestion process.

Pre-treatment of Food Wastes by Thermal Hydrolysis

Pre-treatment of low-quality food wastes (e.g. citrus peels, fruit rinds and vegetable peelings) by thermal hydrolysis was shown to improve the AD of these materials.

Thermal hydrolysis pre-treatment increased the biodegradability of the difficult to digest organic waste from 21% to 77%, and increased biogas yields by 5.5 times over the untreated slurry.

The net result of these findings is that thermal hydrolysis could be used to convert food wastes normally ill-suited for AD into additional, easily digested feedstocks that could help California reach its diversion goals.

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 technology demonstration, the project team developed

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[1] Carollo, (2019). Co-digestion Capacity in California. Retrieved from https://www.waterboards.ca.gov/water_issues/programs/climate/docs/co_digestion/final_co_digestion_capacity_in_california_report_only.pdf

a comprehensive presentation targeted for industry professionals, utility operators and regulators to share project findings and outcomes. The findings from this study have been presented or accepted for presentation in the following conferences:

- SWANA Western Regional Symposium: April, 10, 2019, Yosemite CA
- WasteExpo: May 6, 2019, Las Vegas NV
- CASA Biosolids Seminar: September 11, 2019, Oakland CA
- CWEA Biosolids Seminar: September 17, 2019, Los Angeles CA
- BioCycle REFOR 19: October 29, 2019, Madison, WI
- Global Waste Management Symposium: February 24, 2020, Indian Wells, CA
- WEF Residuals and Biosolids: May 2020, (Video presentation) Minneapolis, MN
- SWANA Western Regional Symposium: March 2021, (Video presentation) Seaside, CA
- WEAO Technical Conference and Symposium: November 9, 2021, London, ON, Canada

An added component of the project's outreach objectives was to physically demonstrate the feasibility of the technology to interested groups and several site tours and presentations were conducted during operations to showcase the process.

Tours	Date
CASA tour following the Biosolids Seminar	September 18, 2019
California Special Districts Association, Santa Barbara Chapter	October 28, 2019
Air and Waste Management Association (AWMA) tour during the Climate Change conference	December 10, 2019
UCSB student tour	December 19, 2019
SCAP tour following the April biosolids committee (canceled due to COVID-19 social distancing measures)	Originally planned April 30, 2020

This report presents data and shared lessons learned that will assist other WWTPs in the development of food waste processing programs. The project featured design and fabrication of skid-mounted systems including a de-packaging and slurry processing technology new to North America, two test-sized anaerobic digesters, and a thermal hydrolysis process (THP) for testing and research purposes. The results presented in this report can provide guidance to estimate food waste preprocessing efficiency, AD loading, biogas production, and thermal THP benefits at other sites. In addition, the report includes practical operational recommendations for organics preprocessing, AD, and THP.

Benefits to California

According to a 2019 study prepared for the California State Water Resources Control Board[2], California WWTPs have enough excess anaerobic digester capacity to process up to 2.4 million tons of diverted organic waste. These organic wastes could be co-digested with municipal sludge, or processed in food waste only mono-anaerobic digesters.

The results of this project showed that compared to the co-digestion data presented in the California State Water Resources Control Board study[3], mono-digestion of these diverted organics could yield greater benefits than processing them by co-digestion at WWTPs. These benefits include:

1. **Increased Energy Recovery**: An estimated 113 megawatts (MW) of energy could be produced from co-digestion of the 2.4 million tons of organic waste. In this study, the data showed better conversion of food waste to biogas, indicating more electricity could be produced. In this operations scenario, using food waste-only digestion could provide up to 120 MW of power production annually, an increase of 6%, or 7 MW.
2. **Reduced Greenhouse Gas Emissions**: Food waste only digestion could create further GHG emission reductions than those available by co-digestion. In California, the additional emissions avoided annually could be up to 14.5 billion tons of carbon dioxide equivalent.
3. **Revenue Generation for WWTPs**: The economic analysis for the project showed that WWTPs in California could generate revenue by receiving diverted and processed organic waste and generating electricity with the produced biogas. Generally, revenue will vary for each WWTP and will depend on plant scale, tipping fees, energy prices, and available renewable energy credits. As public utilities, this value creation could have a positive impact on ratepayers, such as reduced rates, which would result in a net benefit to the community.

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[2] Carollo, (2019). Co-digestion Capacity in California. Retrieved from https://www.waterboards.ca.gov/water_issues/programs/climate/docs/co_digestion/final_co_digestion_capacity_in_california_report_only.pdf

[3] Ibid

CHAPTER 1:
Introduction

Background

An increasing number of states and provinces throughout North America have implemented organics bans or set aggressive diversion targets from landfills to support greenhouse gas (GHG) emission reduction goals. In California, Assembly Bill 1826[4] requires businesses to recycle their organic waste depending on the amount of waste they generate per week. Senate Bill 1383[5] establishes targets to reduce statewide disposal of organic waste by 50% below 2014 levels by 2020 and 75% by 2025. These legislative initiatives require the separation, collection, and processing of organic waste from commercial, institutional, and residential sources.

Based on the CalRecycle 2014 Waste Characterization Study (Cascadia, 2015), organic waste represents two-thirds of solid waste disposed at landfills in California, with food waste alone accounting for approximately 18% (5-7 million tons annually statewide). To reach the mandated diversion target "CalRecycle estimates that 27 million tons will have to be redirected from landfills in 2025, including edible food and approximately 18 million tons of organics waste will need to be processed at compost, anaerobic digestion (AD), or chip-and-grind facilities."[6] Assuming 50 to 60% of disposed food waste (FW) can be recovered for digestion, the State Water Resource Control Board (SWRCB) estimates that 3.3 to 4.4 million short wet tons of food waste will be available for digestion in 2025[7].

Digestion can take place at standalone AD facilities or at existing WWTP digesters where food waste can be digested/co-digested with sludge. According to United States Environmental Protection Agency (US EPA)[8] Region 9, "almost 140 WWTPs use anaerobic digesters, with an estimated excess capacity of 15-30%". Based on a survey of 59 California WWTP with an AD process, SWRCB estimates the minimum statewide excess AD capacity can accommodate 2.4 million short wet tons of diverted food waste[4].

In addition to AD, other key systems must be in place and have sufficient capacity including: a receiving station suitable for food waste slurry, a dewatering system to manage the digestate, as well as a biogas conditioning and flare system to safely and beneficially manage the additional biogas.

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[4] https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140AB1826&search_keywords

[5] https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB1383

[6] CalRecycle, (2020). Analysis of the Progress Toward the SB 1383 Organic Waste Reduction Goals.

[7] Carollo, (2019). Co-digestion Capacity in California. Retrieved from https://www.waterboards.ca.gov/water_issues/programs/climate/docs/co_digestion/final_co_digestion_capacity_in_california_report_only.pdf

[8] USEPA, (2017). Turning Food Waste into Energy at the East Bay Municipal Utility District (EBMUD). Retrieved from https://19january2017snapshot.epa.gov/www3/region9/waste/features/foodtoenergy/wastewater.html

Leveraging existing AD capacity at WWTPs enables projects to come online faster and at a lower cost than developing new standalone facilities since the infrastructure (digester, dewatering, biogas handling, and wastewater treatment) and onsite expertise already exist. Organic waste diversion projects at WWTPs require limited capital improvements, including food waste receiving facilities and AD upgrades to improve mixing and heating. These projects minimize the impact of transport because WWTPs are often located closer to dense urban areas where food waste is generated, while composting facilities and landfills are typically remote and farther away. In addition, processing food waste can offer additional revenues to the WWTPs through increased biogas (and thus energy) generation and tipping fees.

Increased biogas and power production can be a major driver for utilities considering that "energy costs for water and wastewater can be 1/3 of a municipality's total energy[9]". Across the United States (US), it is estimated that "municipal wastewater treatment systems use approximately 30.2 billion kWh per year or about 0.8% of total electricity use in the US [10]".

However, as highlighted in a recent March 2020 Water Environment & Technology article[11], "adoption is limited [with] fewer than 1 in 10 of 14,000 water resource recovery facilities (WRRF) [in the US] using [AD] to process wastewater solids, and fewer than 1 in 10 of those co-digesting food wastes". Water resource recovery facilities are designed with excess capacity to handle potential fluctuations in wastewater flows due to extreme weather and population growth and are hesitant to give it up. In addition, facilities are often reluctant to receive new feedstocks due to concerns over contaminants which may clog or damage piping and pumps, increased contaminant accumulation in digesters reducing overall residence time, potential toxic side-effects which may upset the digesters microbial activity, potential for odors, permitting requirements, and increased quantity of biosolids requiring further management. This pilot project at Goleta Sanitary District (GSD) addresses several of these concerns using mobile skid-mounted units, including depackaging (separation of food waste from non-organic materials), AD, thermal hydrolysis, and energy conversion technologies.

Goals and Objectives

The overall purpose of the project was to demonstrate that it is possible to divert organic waste from landfills by using existing assets at water resource recovery facilities as a means to help California reach its diversion goals. This was achieved by demonstrating that it is possible to pretreat source-separated organic (SSO) waste as feedstock for AD at wastewater treatment plants (WWTPs) resulting in enhanced operational efficiencies for AD and increased digester gas production.

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[9] USEPA, (2008). Ensuring a Sustainable Future: An Energy Management Guidebook for Wastewater and Water Utilities. Retrieved from https://nepis.epa.gov/Exe/ZyPDF.cgi/P1003Y1G.PDF?Dockey=P1003Y1G.PDF.

[10] EPRI, (2013). Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Retrieved from https://www.waterrf.org/system/files/resource/2020-03/4454.pdf.

[11] Jones, (2020). Food Waste Co-Digestion at Water Resource Recovery Facilities. Water, Environment & Technology. Retrieved from http://www.waterenvironmenttechnology-digital.com/waterenvironmenttechnology/march_2020/MobilePagedArticle.action?articleId=1568299#articleId1568299.

The technical goals of the project were to:

- Demonstrate a thermal hydrolysis technology that can substantially increase volatile solids (VS) breakdown resulting in increased biogas yield from food and organic wastes.
- Demonstrate a depackaging technology that produces a digester feedstock that is nearly free of contaminants (e.g. metals, plastics, glass) from SSO. "Nearly free of contaminants" was defined as a digester feedstock with less than 0.1% contamination on a mass basis.
- Demonstrate how the combined technologies of depackaging, thermal hydrolysis and AD can work together to produce a product that is significantly free of contamination, that is easily digested without upsets to the AD and convert it into biogas and ultimately energy.
- Demonstrate that when processed organic waste is anaerobically digested, 30% more biogas is produced per unit dry mass.

By the demonstrating the above goals, the project would show ratepayer benefits of greater reliability and lower costs, demonstrate technical advancements and breakthroughs to overcome barriers to State energy goals, and increase WWTP operator confidence in accepting feedstock material suitable for co-digestion.

The project focused specifically on food waste digestion only, as the economic incentives, particularly the eligibility of food waste-only digestion for D3 Renewable Identification Number (RIN) credits, are greater.

CHAPTER 2:
Literature and Technology Review

Food Waste Preprocessing

Current organics pre-processing solutions can broadly be categorized into three types: extrusion, pulping, and milling.

Extrusion

Extrusion technologies are high-pressure systems that extrude organics against mesh plates. Water is added afterwards to dilute the resulting organic cake, and grit particles are removed. Specific extrusion technology examples are Anaergia's Organics Extrusion Press (OREX™) and Athens Services Organic Separation Press (OSP). Several Anaergia OREX presses are in operation at full-scale facilities in California. According to the manufacturer, the press can recover more than 90% of putrescible organics from mixed waste streams.

Pulping

Pulping technologies mix food waste with process water, allowing for density-driven separation of light materials (e.g. plastics) and heavy materials (e.g. bones, metal objects), followed by grit removal. Specific examples include the BTA® Waste Pulper. While there are no pulpers installed in California, they are in existing facilities in North America such as the City of Toronto Disco Road Facility in Canada. According to the manufacturer, the pulper produces a pumpable organic suspension containing 90% fermentable biomass components of the waste.

Milling

Milling technologies use paddles or hammers to batter food waste and isolate organics through a mesh, followed by grit removal. There are several specific technology examples including DODA's Bio Separator, Scott's THOR Turbo Separator, Cesaro Mac. Import's Tiger, and SMICON's SMIMO de-packaging machines. While there are hundreds of SMICON machines in operation worldwide since 2006, the 5-ton per hour (tph) test unit installed as part of this project is the first in the US. According to the manufacturer, the SMIMO unit can produce a clean organic slurry with less than 1% contaminants from SSO.

The technology of the SMICON system offered an easy-to-implement and operate unit for the project. Maintenance requirements are low, and energy consumption was limited due to the reduced hours of operation needed to process the anticipated volume of feedstock material.

In addition to the core process using extrusion, pulping, or milling, a combination of preprocessing methods is usually required to prepare the waste stream (e.g. bag opener) or polish the organics slurry (for example, magnets to remove metals, hydrocyclones to remove grit).

Food Waste Anaerobic Digestion

Anaerobic digestion is currently the most efficient commercial-scale technology for beneficially using food waste. Its end products are nutrient-rich digestate, which can be used as a soil amendment, and biofuel that can be converted to electrical and heat energy. Conventional practice in the US has been to co-digest food waste at a relatively low solids fraction with sewage sludge to maintain process stability. Mono-digestion of food wastes is much more common in Europe, particularly the United Kingdom[12]. Commercial scale FW mono digestion has also been demonstrated in North America[13]. The City of Toronto's Dufferin Organics Processing Facility has been operational since 2002, and in 2016 construction began to double its SSO processing capacity from 25,000 tonnes/year to 55,000 tonnes/year[14] (City of Toronto).

Food waste has been typically co-digested as the inclusion of co-substrates helps improve process stability. However, research over the last decade has shown that process instability was often caused by deficiencies in trace nutrients. It has also shown that with careful supplementation, mono-digestion of food wastes can be accomplished at high organic loading rates (0.3 lb VS/cu.ft/d) and achieve 80% or more of the biochemical methanation potential (BMP)[15], at methane yields between 0.42 – 0.47 m^3/kgVS. These values are at the upper range of methane yields presented in a review[16] which reported yields between 0.293 m^3/kgVS – 0.439 m^3/kgVS.

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[12] Banks, C.J., Heaven, S., Zhang, Y., Baier, U. (2018). Food Waste Digestion: Anaerobic Digestion of Food Waste for a Circular Economy. Murphy, J.D. (Ed.) IEA Bioenergy Task 37, 2018: 12

[13] Van Opstal, B. (2006) Evaluating AD System Performance for MSW Organics, *BioCycle Energy*, 35, November 2006

[14] City of Toronto, (2018). Dufferin Organics Processing Facility. Retrieved from https://www.toronto.ca/community-people/get-involved/public-consultations/infrastructure-projects/dufferin-organics-processing-facility/

[15] Mehariya, S., Patel, A.K., Obulisamy, P.K., Punniyakotti, E., Wong, J.W.C. (2018). Co-digestion of food waste and sewage sludge for methane production: Current status and perspective, *Bioresource Technology*, 265, 519-531, 2018

CHAPTER 3:
Method

Overall Project Approach

Pilot-scale food wastes digestion was conducted at the GSD facility located in Goleta, California. The overall approach of the program was to receive SSO material from a single source at the University of California, Santa Barbara (UCSB); preprocess the SSO into a slurry suitable for digestion; feed the slurry on a continuous basis to two pilot-scale AD (Digester 1 and Digester 2); and quantify the biogas produced in the process.

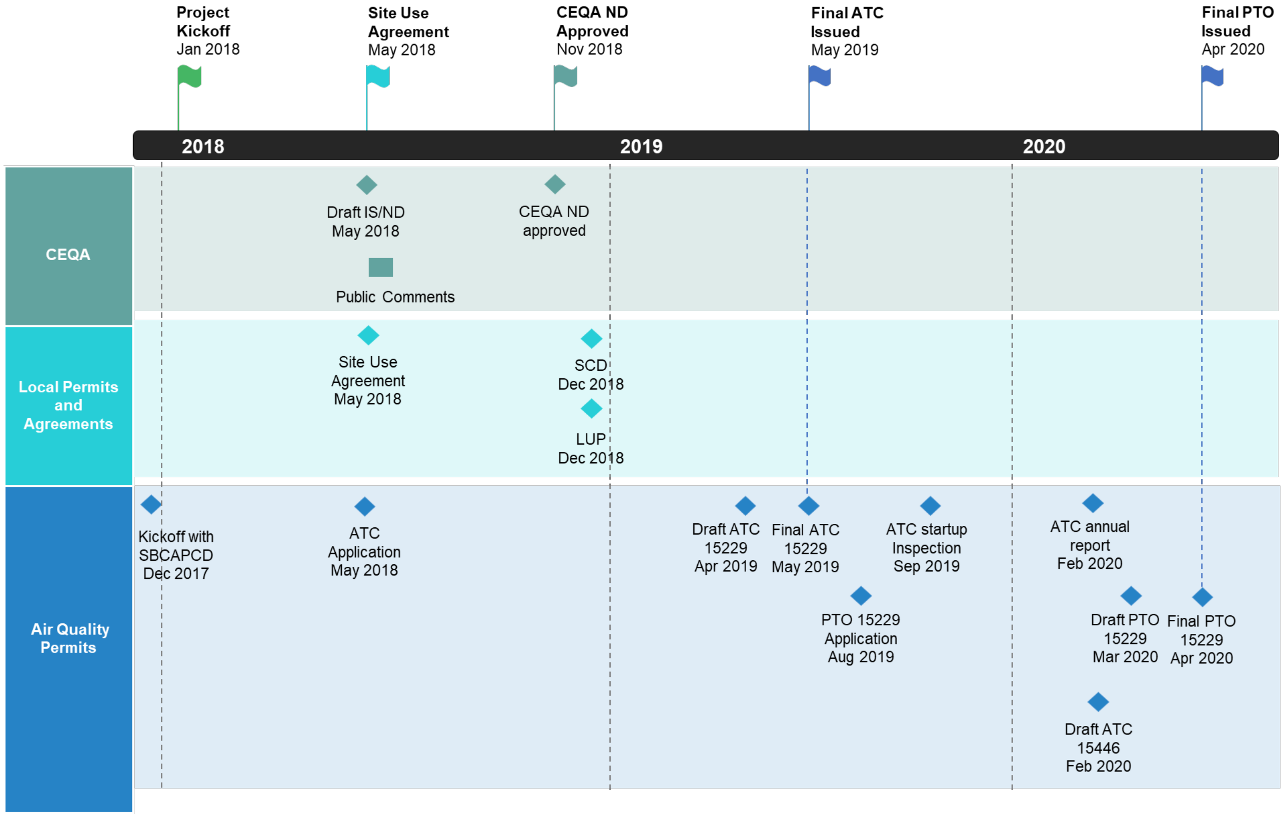
The test plan was designed to seed the pilot digesters with GSD digestate and then feed SSO slurry on a continuous basis, meeting a prescribed volumetric chemical oxygen demand (COD) loading rate. Volumetric COD loading was to be increased on a weekly basis over a 12-week period, until the digesters reached the ultimate COD loading rate. Once that rate had been achieved, the digesters were run at steady state for the remainder of the program.

After achieving steady state digestion operations, the testing plan included feeding the digesters SSO slurry that had been hydrolyzed in the Lystek THP Reactor, while continuing to quantify the biogas generated.

Permitting

To conduct the project, a number of permits were obtained. These included a site use agreement with GSD, California Environmental Quailty Act (CEQA) approval, Authority to Construct (ATC) and Permit to Operate (PTO). The latter two were granted by the Santa Barbara Air Pollution Control District. The overall timeline is summarized in Figure 1.

Figure 1: Overall Permitting Timeline



Source: Lystek International

Project Site

The project is located at the GSD WRRF, at 1 William, Moffett Pl, in Goleta, California. The site is adjacent to the City of Santa Barbara Municipal Airport to the west, the City of Goleta to the north and east, and the Goleta Slough and Pacific Ocean to the south. The district, established in 1942 with approximately 1,500 residents, currently serves a population of about 80,000 people, including UCSB, with annual recent average daily flow of approximately 5 million gallons per day (MGD).

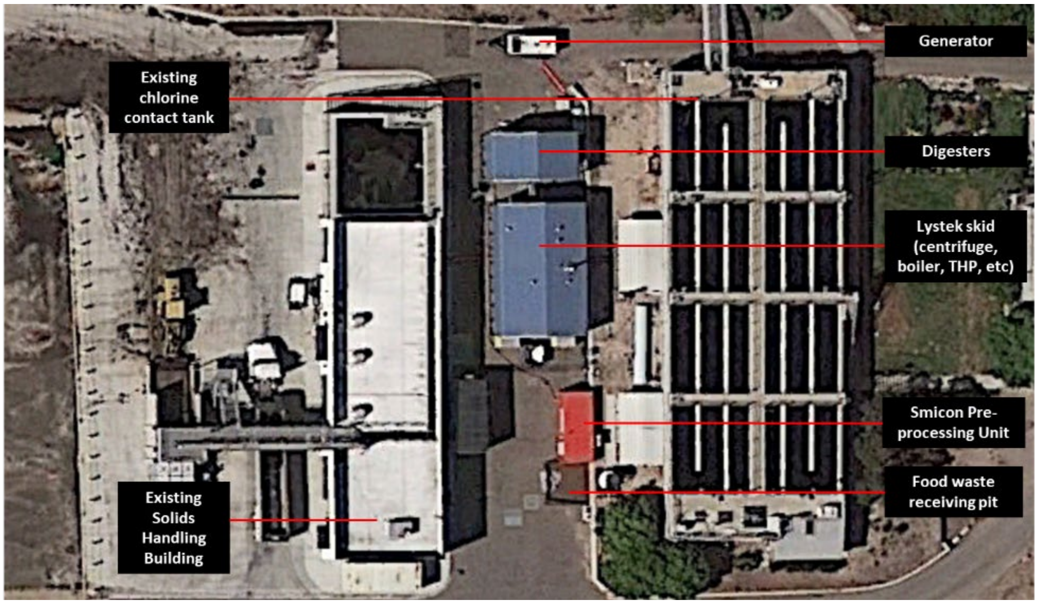
GSD is a special district and has a history of progressive approaches to wastewater treatment technologies. GSD is already a local leader in supplying high-quality recycled water to a variety of area users. GSD recently re-identified itself as a WRRF to better capture its direction as a regional leader in innovation and energy stewardship. One of their primary objectives is to be energy-independent by means of self-generating power to operate all facets of site operations. The technologies implemented in this pilot project represent an opportunity to attain energy neutrality and reduce future fossil-fuel exploration in the sensitive California environment.

Figure 2 provides an overview the system’s location on site. In Figure 3, an aerial view of the system is presented.

Figure 2: Project Site

Source: Google Maps. [*https://www.google.ca/maps/@34.4226798,-119.8332544,260m/data=!3m1!1e3*](https://www.google.ca/maps/@34.4226798,-119.8332544,260m/data=!3m1!1e3)

Figure 3: Site Layout



Source: Google Maps. [*https://www.google.ca/maps/@34.4226798,-119.8332544,260m/data=!3m1!1e3*](https://www.google.ca/maps/@34.4226798,-119.8332544,260m/data=!3m1!1e3)

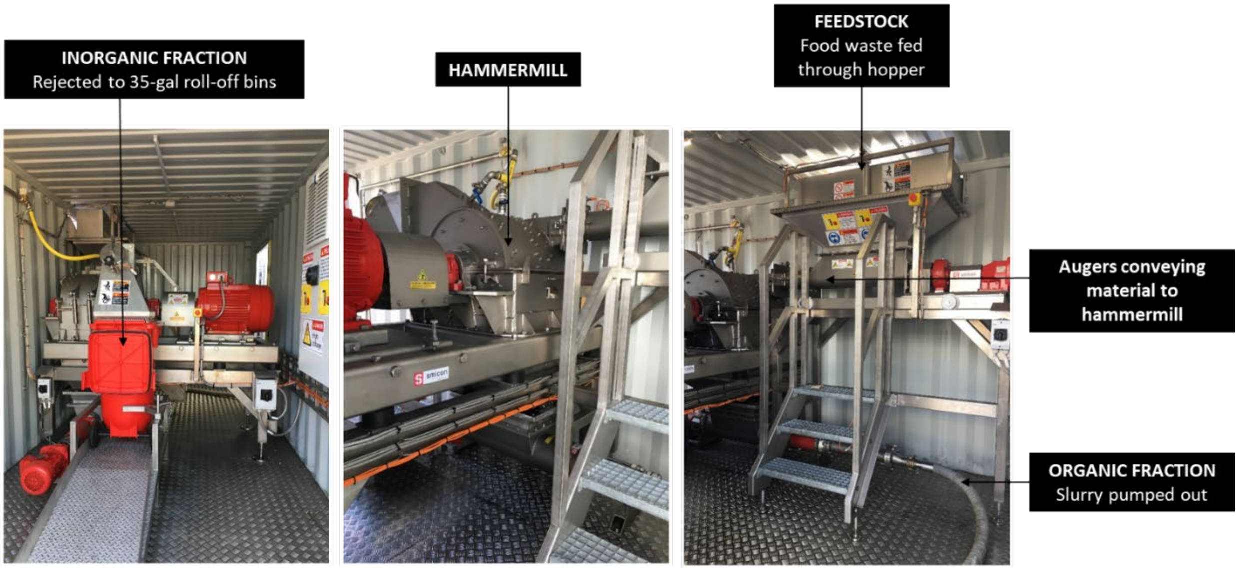
Processing Equipment Description

Preprocessing Skid

The SSO preprocessing unit used in the project was a containerized food de-packaging system (Figure 4). Food waste is fed to the system through the hopper opening on the roof of the container. At the bottom of the hopper, a reversible auger conveys the material into a hammer mill. The mill pulps all the material fed to it, and the organic fraction is separated from the inorganic fraction by the action of a trommel screen. The inorganic fraction is rejected to 35-gallon roll-off bins, while the slurried organic fraction is pumped out of the mill by a progressive cavity pump. The operator can add water to the unit to control variable motor loads due to excessively viscous organic fractions.

The SMIMO30 unit was customized to the project and rated to 5 wet tons/hr. In comparison, industrial-sized units, the SMIMO120 and SMIMO160, are rated at 38.5 wet tons/hr (35 m^3/hr) and 77 wet tons/hr (70 m^3/hr), respectively.

Figure 4: SMICON Preprocessing Unit



Source: Lystek International

Processing Skids

The processing skids consisted of two separate process trains mounted under a shelter (Figure 5): the anaerobic digester system (Figure 6) and the Lystek THP system (Figure 7),

The AD train consisted of:

- Agitated 300-gallon feed tank, 300-gallon digestate tanks, and digester feed pumps.
- Two 2,000-gallon steam heated stand-alone digester tanks.
- Stand-alone flare.
- Process instrumentation to measure pH, temperature, level, and biogas flow.

The Lystek THP system consisted of:

- Centrifuge and polymer system.
- Steam boiler and water treatment system.
- Steam heated Lystek THP Reactor, disperser and support frame, feed and discharge pumps, and product hold tank.
- Process instrumentation to measure reactor temperature, level, product discharge rate.

Figure 5: Covered Processing Equipment

Source: Lystek International Ltd

Figure 6: Digester Equipment

Source: Lystek International Ltd.

Figure 7: Lystek THP Equipment

Source: Lystek International Ltd.

Monitoring and Evaluation Program

During the project, samples were collected for either on site analysis at the GSD lab, or off site at Oilfield Environmental and Compliance (OEC) Inc. Analyses performed at the GSD lab are listed in Table 1. Analyses performed by OEC are listed in Table 2. Due to extended turnaround times with OEC, off-site samples were sent for analysis at Western University in London, Ontario, after October 17, 2019 (Table 3).

SSO slurry (digester feed) was sampled and analyzed for key characteristics: total solids (TS), VS, total and soluble COD, and total nitrogen (TN).

Digesters were monitored for performance by measuring gas production, COD removal, and VS reduction. Digester health was assessed by sampling the digestate and analyzing for VA, TA, and ammonia (NH_3-N).

In addition to the routine analyses listed, a specific methanogen analysis (SMA) was conducted after a process upset to assess inhibition levels in each digester. Last, an extensive suite of BMP tests were performed to help quantify the effects on digestion of hydrolyzing the SSO slurry in the Lystek process. These analyses were also performed at Western University (see Appendix F). Descriptions for each standard method can be found in Appendix C.

Table 1: Analyses Performed on Site at Goleta Sanitary District Laboratory

Parameter	Analytical Method	Samples	Frequency
Total Solids (TS)	SM2540G	Feed and Digestate	Weekly
Volatile Solids (VS)	SM2540G	Feed and Digestate	Weekly
Volatile Acids (VA)	SM5560C	Digestate	Weekly
Total Alkalinity (TA)	SM2320B	Digestate	Weekly

Source: Lystek International

Table 2 lists the analyses performed by OEC.

Table 2: Analyses Performed by Oilfield Environmental and Compliance, Inc.

Parameter	Analytical Method	Samples	Frequency
Total Nitrogen* (TN)	EPA300.0 + SM4500	Feed	Weekly
Ammonia (NH_3-N)	EPA350.1	Digestate	Weekly
COD	SM5220D	Feed and Digestate	Weekly
Soluble COD	SM5220D	Feed and Digestate	Weekly

***TN was determined by measuring total Kjeldahl nitrogen, nitrate and nitrite, and summing the results**

Source: Lystek International

Table 3 lists the analyses performed at Western University.

Table 3: Analyses Performed at Western University

Parameter	Analytical Method	Samples	Frequency
Total Solids	SM2540G	Feed and Digestate	Weekly
Volatile Solids	SM2540G	Feed and Digestate	Weekly
Total Nitrogen*	EPA300.0 + SM4500	Feed	Weekly
Ammonia (NH_3-N)	E350.1	Digestate	Weekly
COD	SM5220D	Feed and Digestate	Weekly
Soluble COD	SM5220D	Feed and Digestate	Weekly

Parameter	Analytical Method	Samples	Frequency
Volatile Acids	SM5560C	Digestate	Weekly
Total Alkalinity	SM2320B	Digestate	Weekly

***TN was determined by measuring total Kjeldahl nitrogen, nitrate and nitrite, and summing the results**

Source: Lystek International

The following field measurements, pH, digesters gas H_2S concentration and food waste slurry TS were taken at the intervals listed in Table 4. FW slurry TS was measured each time a batch of a food waste was processed, and used to set the digester feed pump speeds. The pH was measured as part of the digester health monitoring program. Digester gas H_2S concentration was measured to ensure compliance with the project PTO.

Table 4: Field Data (Goleta Sanitary District)

Parameter	Frequency
pH	3x/week
H_2S	Daily/Weekly
Food waste slurry total solids	1x/feed batch

Source: Lystek International

In order to complete the plant mass balance, the material in and out of the digester were quantified. This was done by collecting real-time data for the feed flow to the digesters and biogas flow from the plant supervisory control and data acquisition (SCADA) system.

CHAPTER 4:
Food Waste Preprocessing

Operating Approach

Bagged SSO was brought to GSD from UCSB via enclosed containers and dumped into a steel receiving bin. Load sizes varied between three to five wet tons. In a normal full-scale deployment, transfer of the received SSO to the preprocessing unit would occur through specialized process equipment. However, due to pilot project size constraints, this was not a feasible solution. As a result, preprocessing operations were a labor-intensive, multi-step process. It included the following activities, shown in Figure 8:

- Delivery and receipt of the SSO in the on-site receiving pit.
- Transfer of the SSO from the pit to the SMICON feed hopper by mini-excavator.
- Manually guiding the bagged SSO into the hopper chute.
- Running and monitoring the SMICON unit to ensure material consistency and quality while filling digester feed tankage.

Preprocessing operations took three operators between five to six hours to process the entire mass of SSO delivered. The weekly volume of slurry required was stored in tanks on site, while any excess was diverted to the AD on site at GSD.

Figure 8: Pre-processing stages

Source: Lystek International Ltd

Operating Results and Discussion

Operational Observations

The preprocessing unit was designed for use in food de-packaging applications. This typically encompasses waste packaged and unpackaged products from supermarkets and the catering industry, or for residual products, condemned products or surplus from food production industries.

However, the material received from UCSB was single and double-bagged, pre- and post-consumer SSO, which proved to be an operational challenge. During initial trial runs with the unit, bagged SSO was fed directly to the system, which proved to be incapable of separating the bags from the organic contents. When fed to the system, the garbage bags were not sheared open as expected, but instead got tangled and completely wrapped around the feed augers, preventing the food waste being separated and reaching the mill. Therefore, prior to feeding the preprocessing unit, it became necessary to manually debag the received SSO to ensure functional operations.

Source-Separated Organics Slurry Screening Test

A material screening test was conducted to determine if the unit would produce a slurry that contained contaminants greater than 5 mm (1/4”) in size at a fraction of <1% by mass. For the purposes of the test, “contaminants” were defined to mean non-food waste, for example, plastic, metal, and paper products. The test was conducted according to the following steps.

1. A portion of an SSO delivery was collected from the receiving bin directly and weighed.
2. The feedstock was de-bagged and processed through the unit. The organic fraction was collected in a clean and empty container and weighed, while the reject fraction was collected in a clean and empty container and weighed.
3. A sub-sample of the organic fraction obtained in Step 2 was collected and weighed.
4. This portion was then dewatered slightly by filtration through cheese cloth, with both the filtered fraction and filtrate weighed.
5. The filtered fraction was then spread on a tarp to air dry for three days. The dried mass was then weighed.
6. A portion of the dried mass was then screened though a #4 Mesh (5 mm) sieve and the fractions visually inspected and hand sorted for contaminants.

The results of the test are presented in Table 5.

Table 5: Source-Separated Organics Slurry Screening Test Results

	Mass (lb)	Dry Weight Biomass (%)	Wet Weight Biomass (%)
Bagged Food Waste	166	N/A	N/A
SSO Slurry Collected	161	N/A	N/A
Reject Fraction	9	N/A	N/A
Mass Slurry Used	31.5	N/A	N/A
Dry Solids Content	6.5	N/A	N/A

	Mass (lb)	Dry Weight Biomass (%)	Wet Weight Biomass (%)
Dried Solids screened	4	N/A	N/A
Contaminants >5mm	0.013	0.20%	0.040%
Contaminants <5mm	0.008	0.13%	0.026%
Unidentified <5mm	0.010	0.16%	0.032%
Total Contaminants	0.031	0.48%	0.099%

Source: Lystek International

As shown, the organic slurry contained less than 1% contaminants by mass of any size. This demonstrated the depackaging unit was able to meet expectations. The "unidentified" portion of the contaminants was assumed to be paper. The contaminants are pictured in Figure 9.

Figure 9: Examples of Contaminants by Particle Size

Source: Lystek International

Pre-consumer waste is likely to have consistently low levels of contamination, but contaminant levels in the post-consumer fraction will depend largely on the care and diligence of students and staff scraping plates after mealtimes.

The screening evaluation provided important results to guide preprocessing operations. The test revealed that there is paper-based material (for example coffee cup sleeves and other paper/cardboard material) that contributes to the slurry fraction. While these particles were smaller than 5 mm, they will not digest easily, which can lead to contaminant accumulation and eventual fouling of the digesters.

The operators also observed glass particles (though larger than 5 mm) in the contaminant fraction of the tested slurry. The presence of glass in the slurry presented a risk to the feed pump elastomers and has the potential to cause unnecessary down time.

Food-Based Contaminants

When operating digestion processes, food-based contaminants are also a concern. Such materials can include highly fibrous materials or gritty materials, such as bone and cartilage. While not observed in the screening test, digester feeding operations were frequently interrupted by pump blockages caused by pieces of bone and cartilage large enough to block the ½″ pump suction ports. Examples are shown in Figure 10.This problem was dining hall dependent, and the ramifications of this challenge are further discussed in the Digester Performance section of Chapter 5.

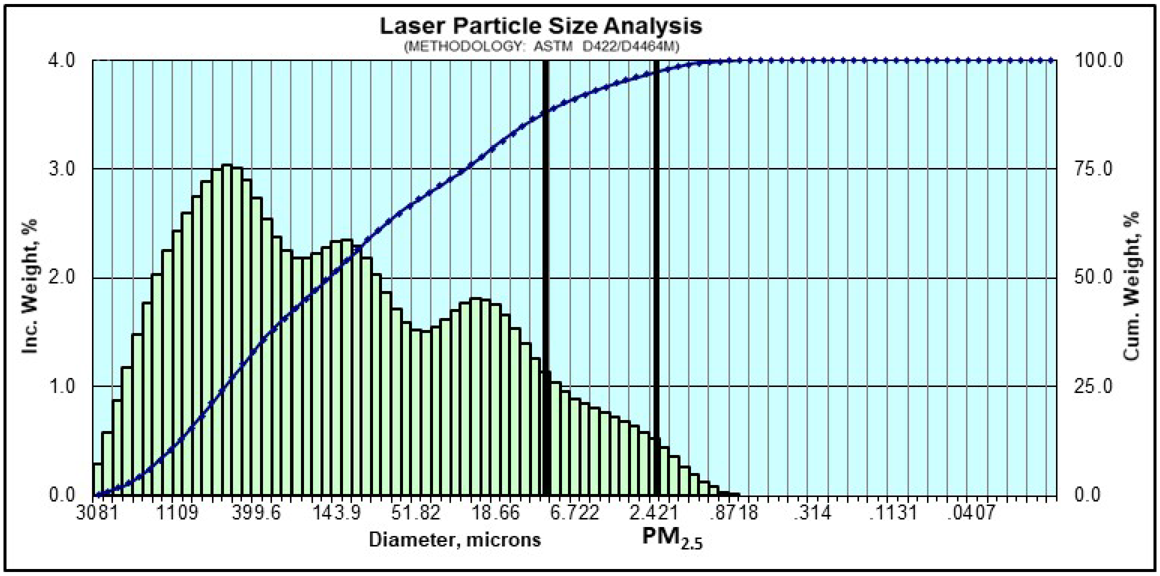
Figure 10: Examples of Food-Based Contaminants Causing Blockages

Source: Lystek International

Particle Size Distribution Analysis

Later in the project, the SSO slurry was sent to Bakersfield Analytical for particle size distribution analysis. The results are presented in Figure 11.

Figure 11: Particle Size Distribution Analysis



Source: Lystek International

The results showed that the particles have a mean/median diameter of 180 microns, which though significantly smaller than the optimum range of particles for AD varying from 0.6 mm[17] to <2mm[18], still contained significant quantities of fats, oil and grease (FOG) and flocculent material that as shown later resulted not only in significant pump and pipe blockage, but also accumulation at the bottom of the digesters.

Operating Adjustments

The operators manually debagged the SSO after it was delivered to the receiving pit. They deemed it prudent to manually sort the debagged waste to remove highly visible glass, metal, and plastic contaminants, and as much paper as possible. Figure 12 shows a typical example of the contaminants removed by hand sorting. While it was a tedious and unpleasant activity, it helped prevent other operational problems downstream.

Figure 12: Typical Contaminants Removed by Hand Sorting

Source: Lystek International

Conclusion

As expected, the pre-processing unit was able to produce an organic slurry with < 1% inorganic contamination by mass. In other existing full-scale food waste digestion plants, there is a multi-step preprocessing train[19]. While not necessarily discrete, these steps can include pulping, large contaminant rejection, grit removal and polishing, and particle size reduction. By contrast, the preprocessing unit used in this project accomplished only the pulping and large contaminant rejection steps. The lack of functionality within the project system to remove gritty contaminants (for example bone fragments and cartilage) caused significant interruptions to digester feeding operations and operational downtime. This underscores the

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[17] Izumi, K., Okishio, Y.K., Nagao, N., Niwa, C., Yamamoto, S., Toda, T., (2010) Effects of particle size on anaerobic digestion of food waste, International Biodeterioration and Biodegradation, 64(7), 601-608, 2010

[18] Parra-Orobio, B. A., Torres-Lozada, P. and Marmolejo-Rebellón, L. F. (2017) Anaerobic Digestion of Municipal Biowaste for the Production of Renewable Energy: Effect of Particle Size. Brazilian Journal of Chemical Engineering ISSN 0104-6632, Vol. 34, No. 02, pp. 481 - 491, April - June, 2017

[19] Van Opstal, B. (2006) Evaluating AD System Performance for MSW Organics, *BioCycle Energy*, 35, November 2006.

need for effective pre-treatment at full scale. Additionally, considering the particle size distribution results, some means of particle size reduction (either by use of a grinder pump or macerator) would have benefitted the program.

With this operational knowledge and experience, WWTP operators will have better confidence in the steps required to receive and sufficiently pre-process organic waste to make it suitable for AD.

CHAPTER 5:
Food Waste Digestion

Testing Approach

The testing approach was to seed Digesters 1 and 2 with digestate from the GSD digesters, and feed SSO continuously on a 24-hour basis to reach a specific COD loading rate.

To ensure successful operation of healthy digesters, a 16-week ramp-up program was devised prior to the start of operations. The purpose of allowing a slow ramp up period was to provide the microbial populations sufficient time to acclimatize to the new feedstock. At 16 weeks, the digesters were to be operating at a volumetric COD loading rate of 7.5 kg COD/m^3/day.

During the proposed ramp-up and steady-state periods, digester health and performance were tracked by measuring influent and effluent TS, VS, and COD, digester ammonia, VA, and alkalinity, and biogas production.

Food Waste Digestion – Results and Discussion

The SSO digestion program ran from August 27, 2019 to April 9, 2020. During the program, four feedstocks were used. These included SSO from the De La Guerra and Carillo dining halls at UCSB, GSD thickened waste activated sludge (TWAS) supplemented with table sugar, and SSO from a local restaurant.

As described in Chapter 4, the de-packaging system was able to effectively separate non-food waste contaminants from the organic fraction during processing of the SSO deliveries. However, the lack of any size-reduction and polishing steps in the preprocessing stage allowed large food waste contaminants and particles to pass to the digester feed tank, which caused regular pump blockages and feed stoppages. To try to overcome this, UCSB SSO sources were changed, which provided limited relief. The ultimate resolution was switching to batch feeding of the digesters. The regular feed stoppages interrupted the ramp-up program, which were exacerbated by additional unforeseen operational challenges and ultimately prevented the digesters from reaching extended steady-state operations.

In a small-scale demonstration project such as this, feedstock logistics also proved critical. In full-scale food waste digesters, feedstock diversity is important to maintain digester health by ensuring essential nutrients. Because of the small scale of this program, broad-based feedstock sourcing was impractical, which necessarily limited feedstock collection to a single source. As a result of this, feedstock characteristics and availability during the program were subject to change based on the source within UCSB and UCSB dining hall seasonal operations.

While helping mitigate the problem of adequate essential nutrients to digesters, variable feedstocks can cause other operational difficulties. In late December 2019, a dose of anti-foam large enough to inhibit the system was added to the digesters. This was an unanticipated event, as digester foaming had not previously been a problem. It is suspected that a build-up of large solid clumps on the surface of the digesters blocked the overflow piping long enough for the liquid level to climb until it triggered the anti-foam system, and delivering the dose. In the weeks preceding the event, feedstock variability was high and the operators observed more fatty material (ground beef) in the SSO than in the early weeks of the program. It is thought that this fatty material likely coagulated in the digesters, eventually causing the blockage. Unfortunately, the inhibition of the digesters was so severe that it necessitated purging, cleaning, and reseeding the digesters, which caused project delays.

However, while UCSB was in session, the logistical challenges of SSO delivery were manageable. Unfortunately, when UCSB ceased campus operations because of normal university holidays (December 2019) and the COVID-19 global pandemic (post-March 2020), SSO deliveries stopped. As a result, feedstock sourcing became so difficult that digester FW operations could not continue which resulted in cessation of the program.

The results of the feedstock analyses, digester health analyses, gas production, and digester performance results are presented and discussed in this section. Where appropriate, results are separated according to the first and second digester seeding.

Feedstock Solids Content

During the program, the influent TS and VS ranged from a high of 135 g/kg and 126 g/kg in the De La Guerra SSO, to a low of 41 g/kg and 38 g/kg in the restaurant SSO. Refer to Appendix D for a plot of the results by week.

Table 6 shows the average TS and VS values for the De La Guerra and Carillo feedstocks, as well as the overall program. Values are also presented for the TWAS+sugar and Restaurant feedstocks, but they are single measurements.

Table 6: Average Total Solids and Volatile Solids Values of the Digester Feedstock

Feedstock	TS (%)	VS (% of TS)	TS (g/kg)	VS (g/kg)
De La Guerra Average	12% ± 2.3%	92% ± 3.8%	116 ± 23.3	108 ± 23.1
TWAS+Sugar	7%	85%	66	56
Carillo Average	8% ± 0.7%	90% ±2.6%	79 ± 6.9	71 ± 4.2
Restaurant	4%	93%	41	38
Program Avg	11% ± 2.4%	92% ±3.8%	106 ± 24.0	98 ± 24.0

Source: Lystek International

The wide variability in feedstock TS/VS and corresponding COD would present challenges in maintaining a constant volumetric COD loading rates, necessitating large variations in influent flows, thus adversely impacting solids digestion. This project attempted to mitigate these variations by operating at a slower feed rate than initially anticipated.

Feedstock COD

Table 7 shows the average COD values and COD-to-VS ratios for De La Guerra and Carillo, and the corresponding single measurements for the TWAS+Sugar and restaurant feedstocks. The COD ranged from approximately 105 g/L to 201 g/L, with a single sample at 280 g/L. Influent COD over the length of the program is shown in Appendix D.

Table 7: Average COD Values of the Digester Feedstock

Feedstock	COD (g/L)	COD/VS (g/g)
De La Guerra Average	173 ± 36.7	1.61 ± 0.32
TWAS+Sugar	167	2.97
Carillo Average	140 ± 37.8	1.97 ± 0.26
Restaurant	105	2.76
Program Average	165.7 ± 37.0	1.69 ± 0.45

Source: Lystek International

Typical values for COD/VS reported in the literature are between 1.0 – 1.45[20,21,22] (Hegde and Trabold, 2019; Banks *et al*, 2018; Kim *et al*, 2015), which are below the range presented in Table 8. The COD/VS ratio for De La Guerra feedstock, derived statistically from a correlation between COD and VS (not shown, R^2 of 0.98), was 1.7, very close to the average value.

The COD/VS ratios for the TWAS+sugar and restaurant feedstocks are well above reported ranges. This suggests that the VS data for each feedstock were underestimated.

The masses of sugar and TWAS volumes added to the digester feed tank during the TWAS+sugar period are summarized. Based on known values for kg COD/kg sugar (1.06), kg COD/kg VS, and the% VS measured for the TWAS, it appears that the single measurement reported was about 14% less than what would have been the expected average over the period.

Table 8: TWAS and Sugar Additions by Date

Date	Volume TWAS (m^3)	Mass Sugar (kg)
2019-12-20	0.59	95
2019-12-30	0.71	100

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[20] Hegde, S., Trabold, T.A. (2019) Anaerobic Digestion of Food Waste with Unconventional Co-Substrates for Stable Biogas Production at High Organic Loading Rates, *Sustainability*, 11, 3875, 2019.

[21] Banks, C.J., Heaven, S., Zhang, Y., Baier, U. (2018). Food Waste Digestion: Anaerobic Digestion of Food Waste for a Circular Economy. Murphy, J.D. (Ed.) IEA Bioenergy Task 37, 2018: 12

[22] Kim, M., Chowdhury, M.M.I., Nakhla, G., Keleman, M. (2015) Characterization of typical household food wastes from disposers: Fractionation of constituents and implications for resource recovery at wastewater treatment, *Bioresource Technology*, 183, 61–69, 2015

Date	Volume TWAS (m^3)	Mass Sugar (kg)
2020-01-07	0.69	91
2020-01-13	0.69	75

Source: Lystek International

Feedstock Total Nitrogen

Feedstock TN is an important parameter, as it can be used to estimate digester ammonia levels. During the program, TN ranged from 5.9 g/L to as low as 0.95 g/L. TN averaged approximately 1.75% of COD, similar to the ratio previously reported by Kim *et al*. (2015). A plot of TN in the digester feedstock by week is shown in Appendix D.

Digester Performance

The following sections describe the results of digester performance and digester health measurements.

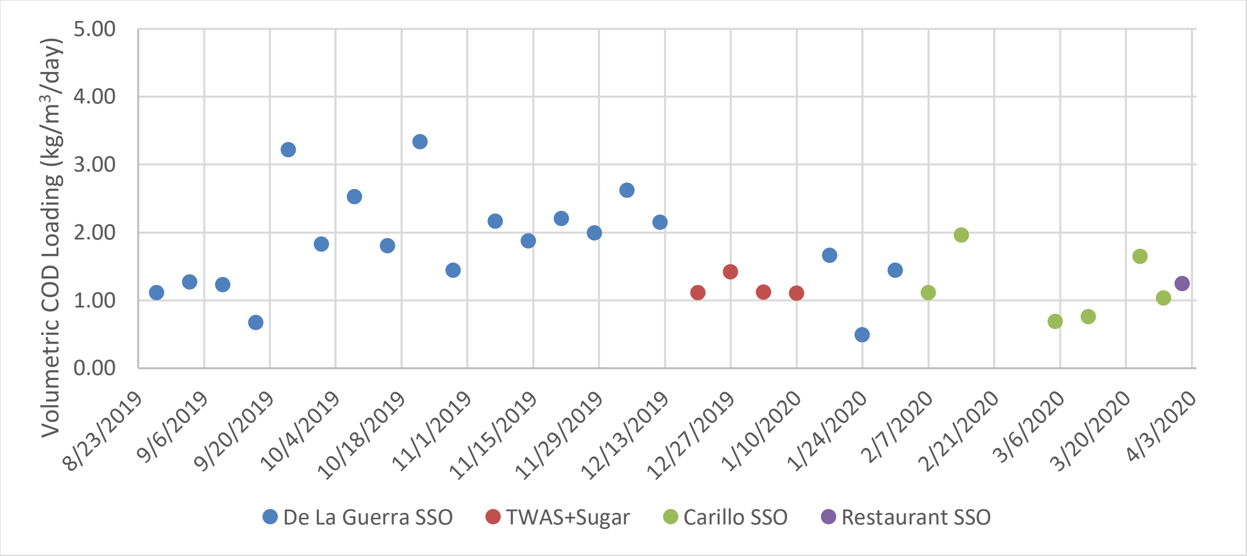
COD Loading

Figure 13 presents the average volumetric COD loading rates achieved during the program, grouped by food waste source.

As shown, the operations did not reach the expected maximum specific COD loading rate of 7.5 kg COD/m^3/day. This was chiefly due to the challenge of maintaining consistent feed pumping to the digesters and as a result of the uneven quantity and quality of organic material received.

The variability in volumetric COD loading was due to two factors: pumping reliability and feedstock COD concentration. Feedstock COD for De La Guerra and Carillo varied by 21% and 27%, respectively.

Figure 13: Volumetric COD Loading Rates by Week



Source: Lystek International

While using De La Guerra derived SSO slurry, digester feeding was impeded by regular blockages of the suction ports to the digester feed pumps, typically by large bone fragments or pieces of cartilage. To try and prevent this, the operators began regular inspection and preventive cleaning activities starting the week of September 24, 2019. This resulted in an improvement in pumping operations, denoted by the increase in COD loading. However, blockages still occurred during unstaffed operating hours, delaying the ramp-up schedule.

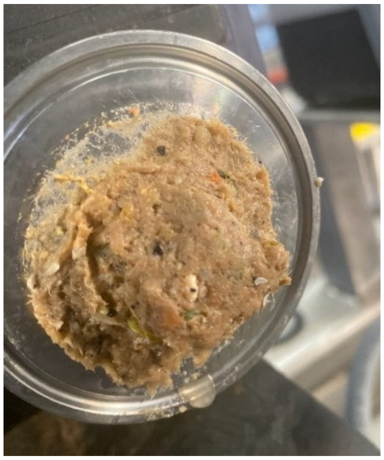
To further improve pumping, tests were conducted to see if the large contaminants could be removed from the slurry using a site-built screening apparatus (Figure 14) consisting of a wood frame and 0.46” opening wire screen. Unfortunately, the fibrous portion of the slurry caught on the screen and plugged it, making the trial unsuccessful.

Figure 14: Screening Apparatus Before and After Screening Test

Source: Lystek International

After struggling with the De La Guerra SSO, the SSO source was switched to the Carillo dining hall, which had a greater proportion of plant-based menu options, anticipating better pumping operations. However, even without the bone and cartilage fragments, regular pump blockages still interrupted digester feed operations. With this feedstock, the problems appeared to stem from the highly fibrous nature of the slurry. It was hypothesized that at the slow pumping rates required for 24-hour feeding, the velocity in the pump suction could have been too slow to maintain homogeneity of the slurry, allowing the fibrous portion to separate and collect in the corners of the non-linear pipe sections at the suction port of the pump (Figure 15).

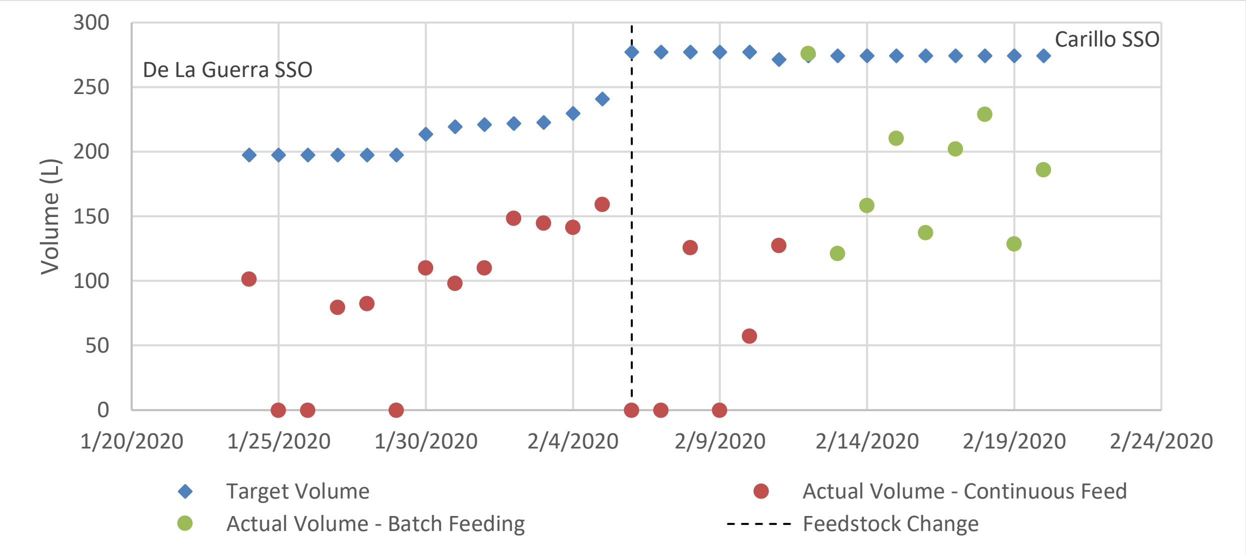
Figure 15: Blocked Digester Feed Pump Suction



Source: Lystek International

To overcome this problem, continuous feeding was abandoned daily batch feeding started February 12, 2020. Figure 16 shows a comparison of continuous and batch feeding modes for the last four weeks of the first seeding. Just prior to the transition, SSO sources were switched from De La Guerra to Carillo, which is also illustrated in the chart. Batch feed volumes were determined from the difference in feed tank levels before and after feeding operations.

Figure 16: Comparison of Continuous and Batch Feeding Modes



Source: Lystek International

Batch feeding improved feeding operations in the following ways:

- No days with zero flow.
- Average batch feed volume (L/d) was 183 ± 51.6 L, a relative variability of 28%. Relative to the target volume, batch achieved 67% of the target volume on average. Average continuous feed volume (L/d) was 78 L/d ± 60.0, a relative variability of 77%. Continuous feeding achieved 34% of the target volume on average.

Variability in feedstock COD also contributed to variability in volumetric COD loading rates. While variation in feedstock COD is to be expected, the challenge was exacerbated by the one-week lag in obtaining lab results.

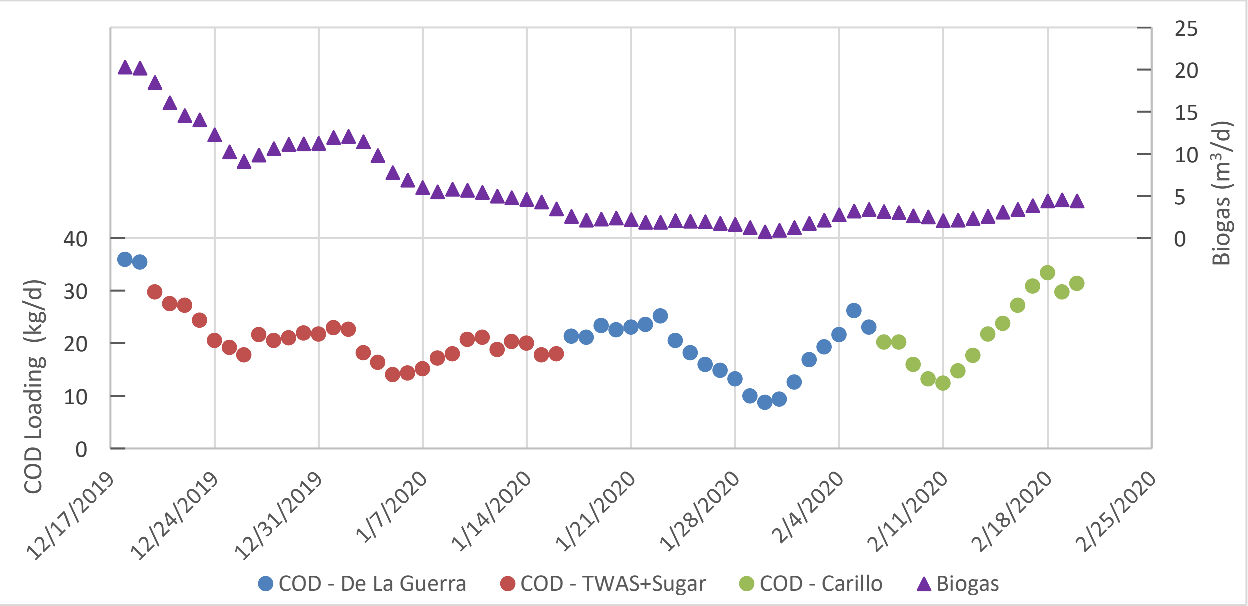
Digester Gas Production

Figure 17 shows rolling 7-day averages for daily gas production (at roughly 37 °C and atmospheric pressure) and COD loading. COD loading is grouped by FW source.

In the gas data presented, flow data for the project are not available until mid-December because the initial selection of biogas flowmeters were not sensitive enough. This was resolved by installing more sensitive flowmeters.

From December 18, 2019 to approximately January 5, 2020, biogas production responded proportionately to the changing COD load, which is to be expected. However, in the week following, biogas production steadily decreased despite increased COD loading. After the week of January 18, 2020, biogas production fluctuated but never exceeded 5 m^3/d despite COD loading approaching 30 kg/d. This suggested that at some point around the end of the December, the digestion process had become severely inhibited. Despite the reduced digester performance, operations continued until mid-February in an attempt to resuscitate the digesters while further investigation into the causes of the inhibition were underway.

Figure 17: Rolling 7-Day Averages for Daily Gas Production and COD Loading



Source: Lystek International

Figure 18 presents cumulative biogas, cumulative COD and biodegradability to methane from December 12, 2019 to February 20, 2020. Biodegradability is calculated by dividing the measured biogas volume by the volume of biogas expected based on 100% conversion of the COD fed to the digester into biogas. It is given by the following equation:

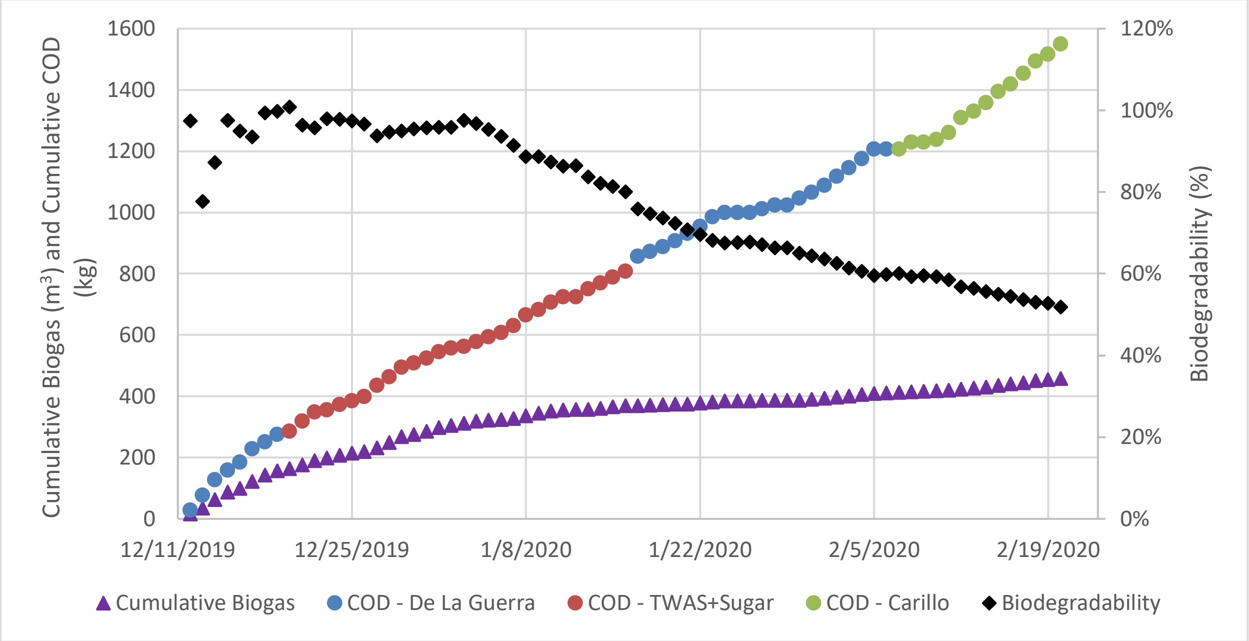
$$\text{Biodegradability} = \frac{V_{measured}(\%\,CH_4)}{M_{COD}\left(0.37\,\frac{\text{m}^3\text{CH}_4}{\text{kgCOD}}\right)}$$

where $V_{measured}$ is the volume of gas measured (in m^3) M_{COD} is the mass of COD fed to the digester (in kg) and $\%CH_4$ is the percentage of methane in the biogas.

Figure 18 illustrates that from December 12, 2019 to January 3, 2020, the digesters had converted 98% of the COD fed. After that date, digester performance decreased, as indicated by the flatter portion of the biogas curve.

Taken separately, the biodegradability for the De La Guerra SSO was 97%, and the TWAS+sugar 92%.

Figure 18: Cumulative Biogas, Cumulative COD, and Biodegradability



Source: Lystek International

Note that the 98% biodegradability during this period is too high based on the feedstock to the digester. During the TWAS+sugar feeding period, the TWAS contribution to COD fed was about one-third, which typically degrades by about 50% in normal digester operations. Assuming the digesters degraded all the sugar, it is expected that the theoretical biodegradability for the TWAS+sugar is 80% at most. Because the calculated average biodegradability for this feedstock was greater than 80%, it would suggest that some of the gas measured was produced from accumulated material in the digester prior to this time period. That said, the results still show excellent performance of the digester, particularly with respect to conversion of SSO from De La Guerra into biogas.

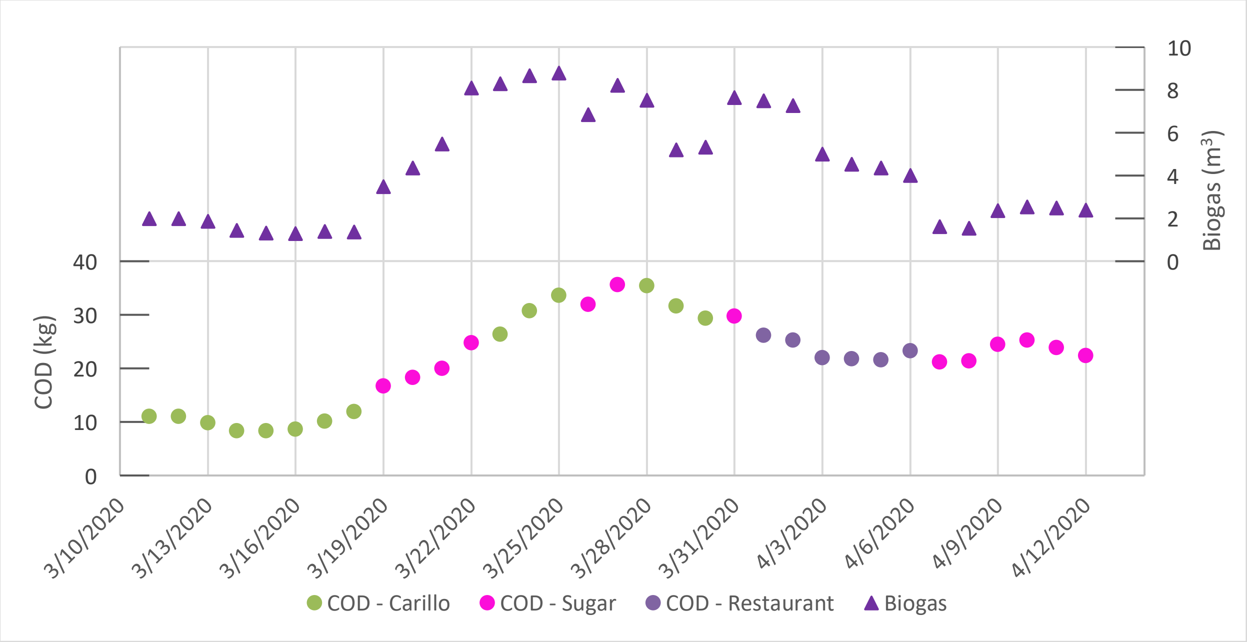
After January 3, 2020, the team noticed during lab analyses that the digestate had a very strong hydrocarbon odor. Reviewing historical operating data and the logbook revealed that a large volume of anti-foam additive had been added to the digesters on January 2, 2020. A site-based test by GSD staff for surfactants showed that surfactant levels in each digester were above concentrations known to be toxic to anaerobic microbes. In mid-February a SMA analysis conducted at Western University confirmed that the digestion was inhibited by 75% – 80% in both the digesters (data not shown).

Between January 2 and February 20, 2020, the system received 992 kg COD but produced only 157 m^3 of biogas, which at 63% methane content translates to around only 27% biodegradation efficiency. Thus, although the anaerobic microbial cultures had not been fully inhibited, it was apparent they were not going to recover, so it was decided to purge and clean the system. This was followed by reseeding the digesters with fresh material.

Cleaning occurred between February 22 and March 2, 2020, with the digesters seeded with fresh GSD digestate the following day. Feeding operations with slurry derived from Carillo SSO began on March 5, 2020. Initial COD loading rates were determined by considering the biogas/volatile solids reduction (VSR) data from GSD and scaling conservatively.

Figure 19 presents the 7-day rolling average biogas production and COD loading.

Figure 19: Rolling 7-Day Averages for Biogas Production and COD Loading

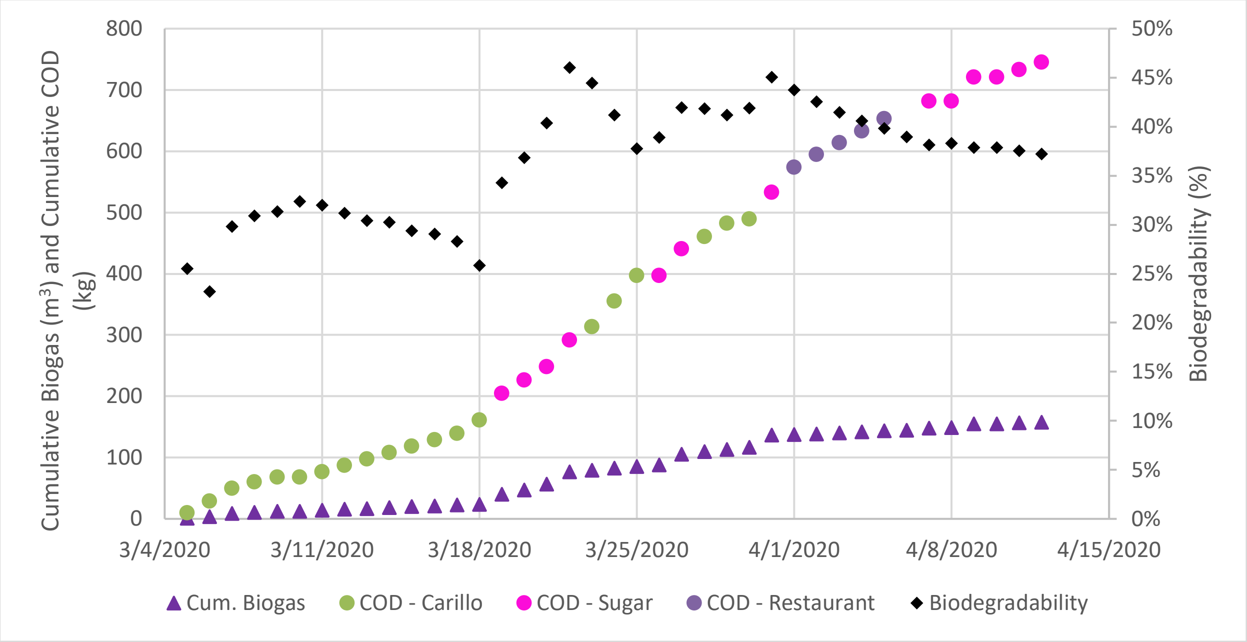


Source: Lystek International

In the COD loading data, the green, pink, and purple circles represent digester feeding with Carillo SSO slurry, table sugar, and the restaurant SSO slurry, respectively.

In the first seeding, biogas production responded proportionately to changing COD loading. During March 10-18, 2020, biogas rates were lower than expected, indicating approximately 35% biodegradability of the Carillo waste, which caused some concern that the second seeding was also inhibited. To test this, table sugar was fed in daily batches (at a rate of 33 kg COD/d) to the digester over four days, which resulted in a large increase in biogas production. Figure 20 presents a graph of cumulative biogas and COD fed over the second seeding.

Figure 20: Cumulative Biogas, Cumulative COD, and Biodegradability (Second Seeding)



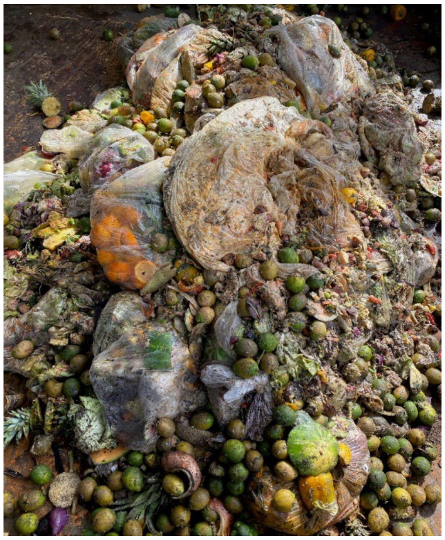
Source: Lystek International

Although biogas production was low on an absolute value, the biodegradability increased from approximately 25% to 32% in the first five days of operation. However, biodegradability did not increase further which would have been expected as the digester acclimatized to its new food source. Sugar addition to the digesters between March 19 and March 22 confirmed the cultures were healthy, as the addition of 87 kg COD produced 37 m^3 of biogas, indicating 76% biodegradation (using 63% average methane content presented below). Following the sugar test, feeding continued with the Carillo SSO slurry, during which time the biogas yield did not improve. Though only qualified visually, the Carillo SSO slurry appeared much more fibrous than the De La Guerra slurry from earlier in the project. The rapidly increasing yield at the start of this trial was likely due to the soluble COD fraction being consumed quickly, while hydrolysis of the large fibrous particles was very slow.

On March 25, 2020, UCSB cancelled dining hall and campus food service because of the global COVID-19 pandemic, and food waste deliveries from UCSB were discontinued. The local hauler was able to source SSO from a local restaurant, which was delivered starting April 1, 2020. The chart above shows biogas yields declined further after the feeding this SSO slurry.

Though not quantified, visual observation of the delivery indicated that this restaurant food waste consisted of a large proportion of fruit scraps, particularly citrus fruits – rinds, peels and stems, with minimal meats and vegetables (Figure 21).

Figure 21: Delivery of Restaurant Source-Separated Organics



Source: Lystek International

While such food waste will show a high total COD value when assayed, chemicals in the peel, such as D-limonene, are known to be inhibitory to AD[23]. Further, AD of citrus fruit, such as oranges, has been shown to produce much lower gas yields than would be expected theoretically[23]. Although proving the exact cause of poor digester performance associated with this SSO was beyond the scope of the program, it appears that the prevalence of citrus fruit could have been a likely reason for low biogas production with this food waste.

Given the limited availability of acceptable food waste, low degradability of the feedstock, and the logistical challenges imposed by the pandemic, it appeared highly unlikely the digesters would be able to reach a high enough volumetric COD loading rate to produce sufficient biogas to convert to energy. At this point the decision was made to explore additional research objectives that were in grasp.

The poor characteristics of the available restaurant SSO presented an ideal chance to assess the effects of Lystek THP process on food waste digestion. The results of this trial are discussed in Chapter 6.

COD Removal, Volatile Solids Reduction, and Unit Gas Production

Influent COD concentration over the program ranged from 105 g/L – 280 g/L, and the effluent COD concentration ranged from 6 g/L – 19 g/L. Influent VS concentration ranged from a low of 38 g/kg to a high of 126 g/kg, with effluent VS concentration ranging between 4.5 g/kg – 11 g/kg. Data for influent and effluent COD and VS, presented by week and grouped by feedstock, are presented in Appendix D. Because digestate quality from the two digesters was comparable, average COD removal and average VSR are presented in Figure 22. The data show that for the duration of the program, average COD removal ranged from 88% – 95%, and average VSR between 86% – 97%. However, these results contradict the previous results,

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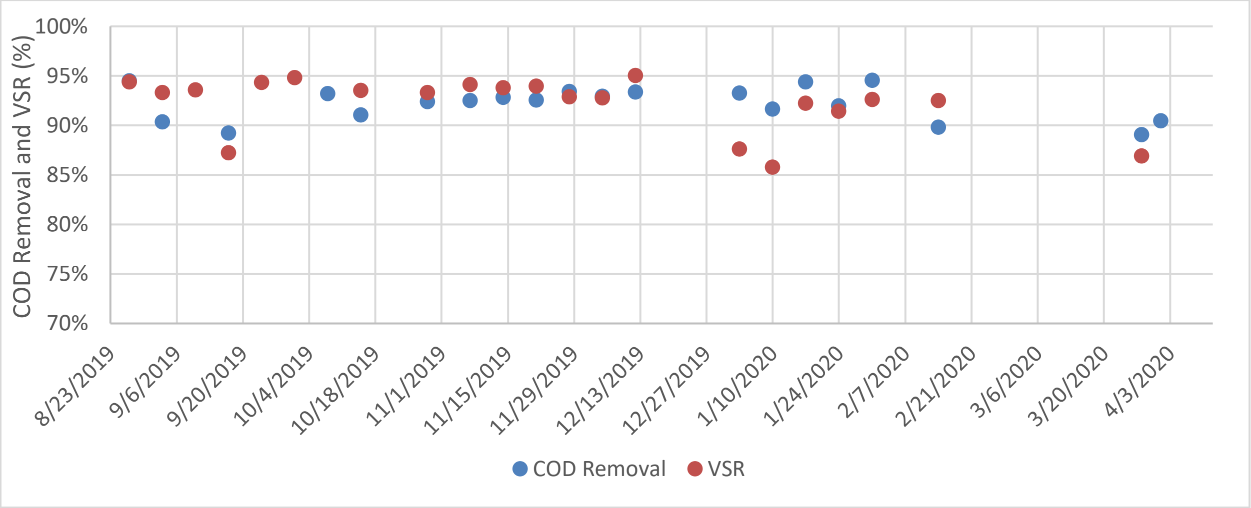
[23] Wikandari, R., Millati, R., Cahyanto, M.N., Taherzadeh, M.J. (2014) Biogas Production from Citrus Waste by Membrane Bioreactor, *Membranes*, 4, 596-607, 2014.

which showed that of the COD fed on a cumulative basis, only 50% was converted to biogas during the first seeding, and 37% converted in the second seeding.

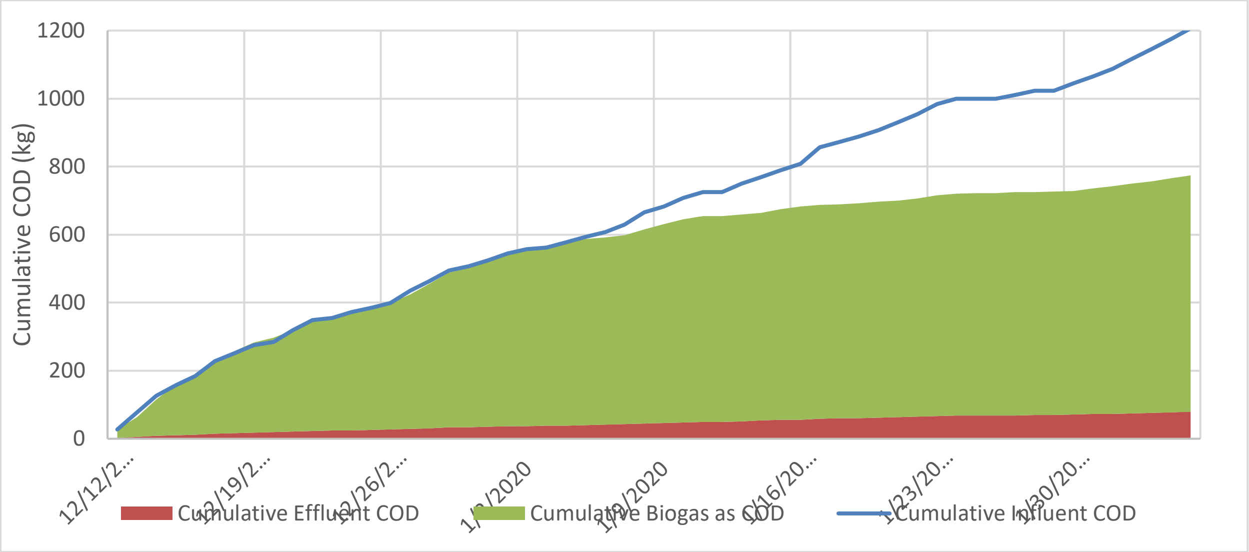
Figure 22: Average Weekly COD Removal and Volatile Solids Reduction



Source: Lystek International

Figure 23 illustrates the COD imbalance with a plot of cumulative influent COD, cumulative effluent COD, and cumulative biogas as COD.

Figure 23: Cumulative Influent COD, Effluent COD and Biogas as Effluent COD



Source: Lystek International

The areas representing cumulative effluent COD and biogas as COD are stacked to visualize the total COD leaving the system, and up until January 4, 2020, the total COD into and out of the system is balanced. After that point, it begins to diverge. The imbalance is due to either over-estimation of gas or under-estimation of effluent COD. The gas meters were calibrated and checked regularly, and the system piping was inspected for gas leaks and found to have none. Therefore, the likely cause of the imbalance was underestimation of the effluent COD.

Throughout the program operators had to remove large clumps of material that would have blocked the digester overflows, shown in Figure 24. Some of the clumps were collected and sent for analysis.

Figure 24: Digester Overflow Blockage and Recovered Clumps

Source: Lystek International

These clumps had a high FOG content (>40%) and smelled of hydrocarbons. While the exact composition was not analyzed, it is plausible that the anti-foam injections would have caused the FOG content of the De Le Guerra SSO to coagulate and form a layer on the surface of the digesters. This would have theoretically been construed as "removed" COD from the digestate which would not have been captured in the COD measurement. Similarly, observable amounts of solid material were found at the bottom of each digester during each cleaning. Examples of solid material in the digester found during cleanout are shown in Figure 25. Unfortunately, the quantities of all this material were not measured, so the degree to which they influenced the lack of mass balance closure was not able to be quantified.

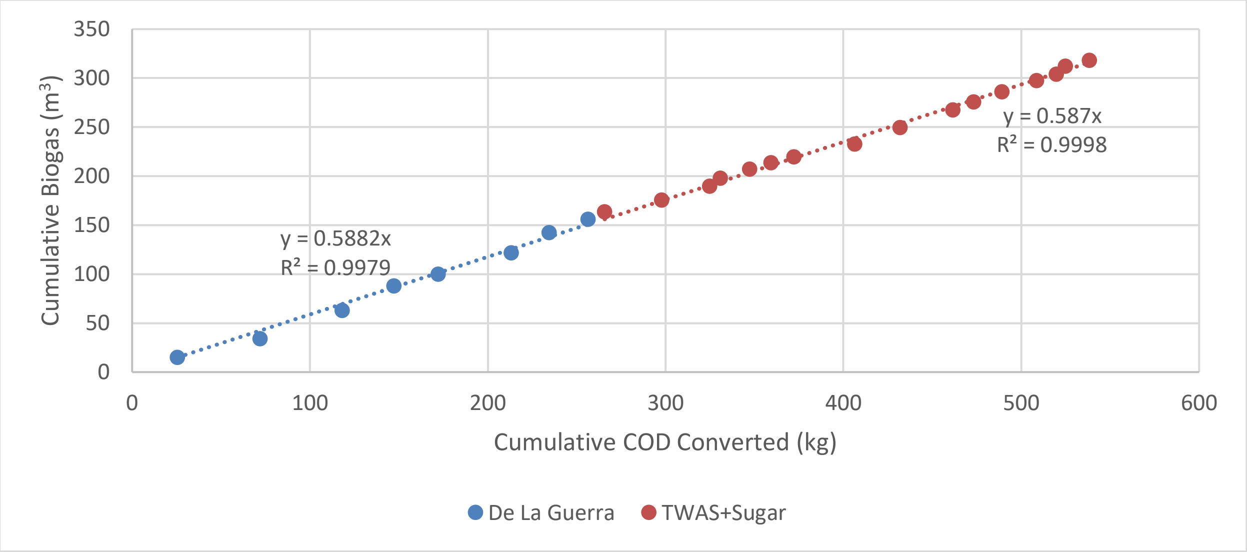
Despite challenges related to mass balance closure during the later program period, biogas yield data from the period before the anti-foam event suggests that the COD conversion and VSR data above from the same period are indicative of good mass balance closure. They can then be used to calculate gas production on a dry unit basis and compared against similar metrics from the GSD.

Figure 25: Solids Observed during Digester Cleanout

Source: Lystek International

Figure 26 presents cumulative biogas vs cumulative COD converted, grouped by feedstock.

Figure 26: Cumulative Biogas vs Cumulative COD Converted (Dec 12. – Jan 3.)



Source: Lystek International

The trendline shows that for the De La Guerra SSO feedstock (December 12 – 19, 2019), m^3 biogas/kg COD converted was 0.59. For the TWAS+sugar (December 20, 2019 – January 3, 2020), m^3 biogas/kg COD converted was 0.59.

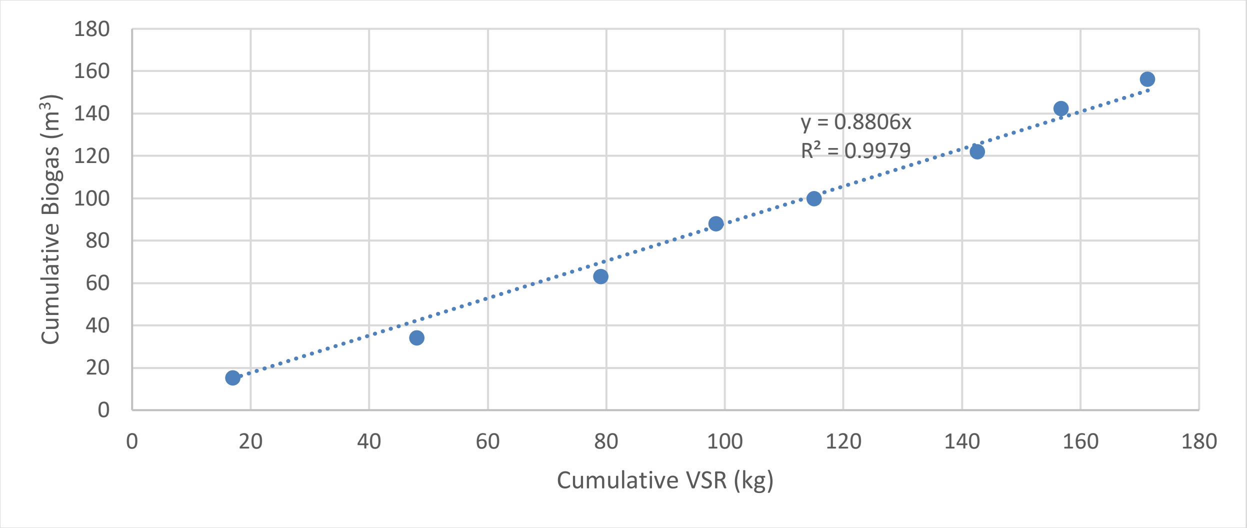
The trendline for the De La Guerra SSO feedstock shows that m^3 biogas/kg VSR was 0.88, as shown in Figure 27. Taken together, Figure 26 and Figure 27 indicate nearly perfect closure of the VS mass balance since biogas production based on COD removed was 0.59 m^3 biogas/kg COD$_r$ and the VS/COD ratio was 1.6, specifically 0.94 m^3 biogas/kg VSR.

Figure 27 presents cumulative biogas vs cumulative VSR for the same period.

The error in the mass balance is 6.4%, calculated from (0.94-0.88)*100%/0.94. This also confirms the excellent mass balance agreement for COD.

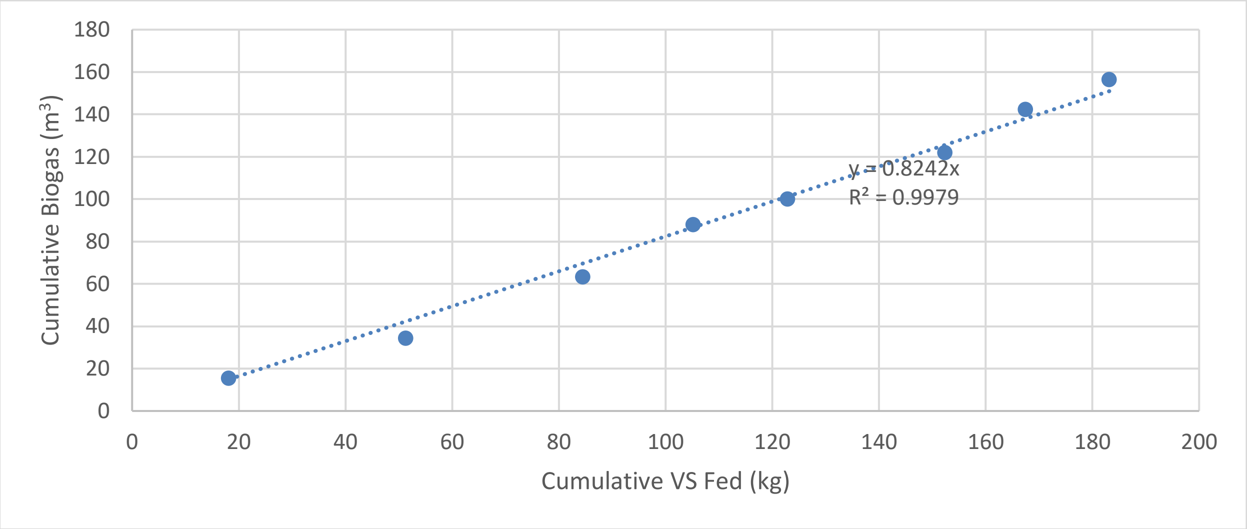
For comparison against the performance of biogas generation from municipal sludge digestion at the GSD, biogas volume/unit mass fed can be compared. Figure 28 presents cumulative biogas vs cumulative VS fed for the De La Guerra period.

Figure 27: Cumulative Biogas versus Cumulative Volatile Solids Reduction for the De La Guerra Feedstock (Dec. 12 – Jan. 3)



Source: Lystek International

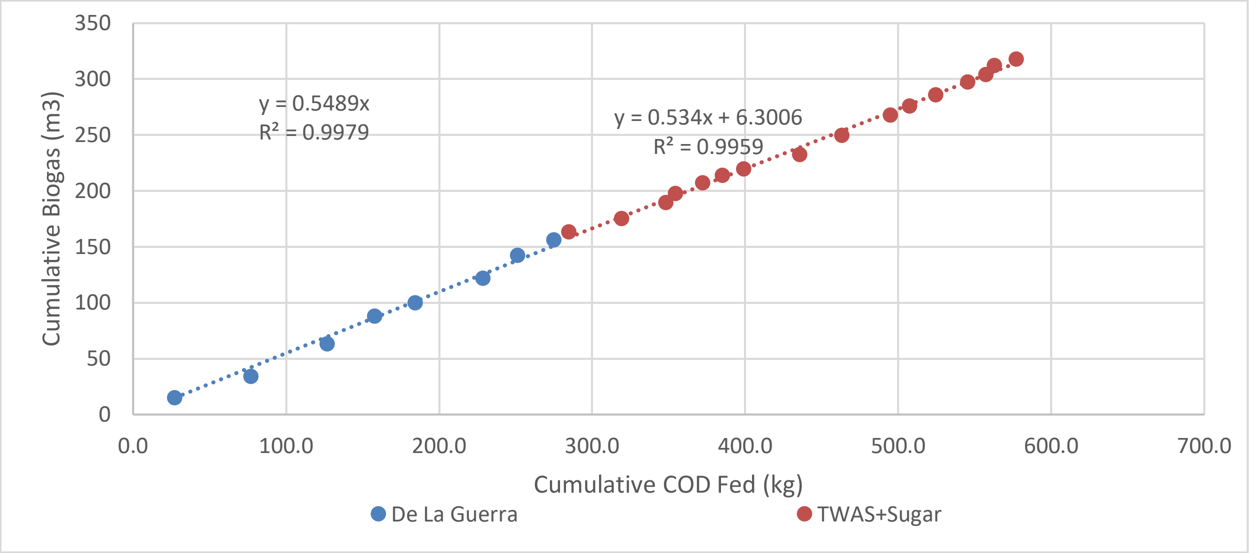
Figure 28: Cumulative Biogas versus Cumulative Volatile Solids Fed for the De La Guerra Feedstock (Dec. 12 – Jan 3)



Source: Lystek International

The digestion of the De La Guerra SSO yielded 0.82 m^3 biogas/kg VS fed to the digester. On the same per unit basis, the GSD digesters yield 0.60 m^3 biogas/kg VS fed (data not shown). Figure 29 shows cumulative biogas vs cumulative influent COD for the De La Guerra and TWAS+sugar.

Figure 29: Cumulative Biogas versus Cumulative COD Fed



Source: Lystek International

The biogas yields were 0.55 m^3 biogas/kg COD fed for the De La Guerra SSO and 0.55 m^3 biogas/kg COD fed for the TWAS+sugar. In a study of cafeteria waste digestion, at volumetric COD loading rates of 1.4 – 4.4 kg COD/m^3/d, the biogas yield was 0.4 m^3 biogas/kg VS fed (Hegdi and Trabold, 2019), approximately half the yield reported above for digestion of the De La Guerra SSO in the study.

Gas Quality – Methane

The biogas produced during the program was analyzed on site by SCS Engineers using a portable analyzer to measure its composition. Methane content in each digester by date is presented in Appendix D. Methane content in Digester 1 ranged from 56% – 70%, with an average of 62.5%. Similarly, methane content in Digester 2 ranged from 59% – 66% with an average of 61.4%, indicating consistent parallel performance in both digesters. Over the entire program, biogas methane content averaged 62 ± 3.7%, which is typical for a food waste digester.

Gas Quality – Hydrogen Sulfide

Dissolved inorganic and organic sulfur species are reduced to H_2S by sulfate-reducing bacteria during AD. The amount of H_2S formed during digestion is dependent on the sulfur content of the food waste fed to the digester, the digester chemistry, as well as any H_2S control measures in place. As part of permitting requirements, the digester gas was measured by Draeger tube for H_2S during the program H_2S levels ranged between 10 – 200 parts per million volume (ppmV), with higher readings corresponding to periods when the SSO was observed to contain high levels of meat scraps. H_2S was controlled by addition of between 800 mL – 1200 mL of 17% ferrous chloride ($FeCl_2$) solution to the digesters. Details are presented in Appendix D.

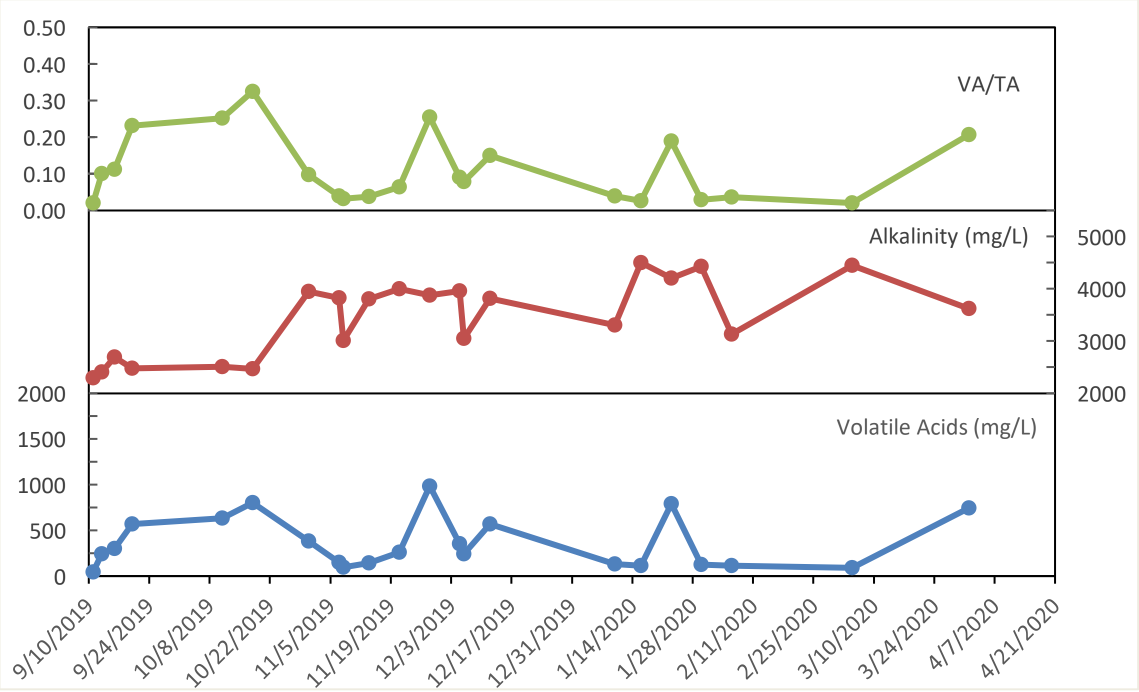
Digester Health

During AD, an imbalance between the acidogenesis and methanogenesis steps can lead to rapid pH decrease and subsequent digester failure. Sufficient alkalinity helps maintain pH and buffer against this phenomenon. To evaluate if there was imbalance in the digester acid production, the digester pH, TA, VA, and volatile acits to total alkalinity (VA/TA) ratios were measured. VA and TA were measured on a weekly basis, while the pH was measured on site roughly every three days.

In typical food waste digestion, alkalinity ranges between 3500 – 4500 mg/L and a VA/TA ratio under 0.3 indicates a healthy digester. As the VA/TA ratio approaches 0.4, it suggests there is inhibition affecting the methanogens, reducing conversion of VA into methane.

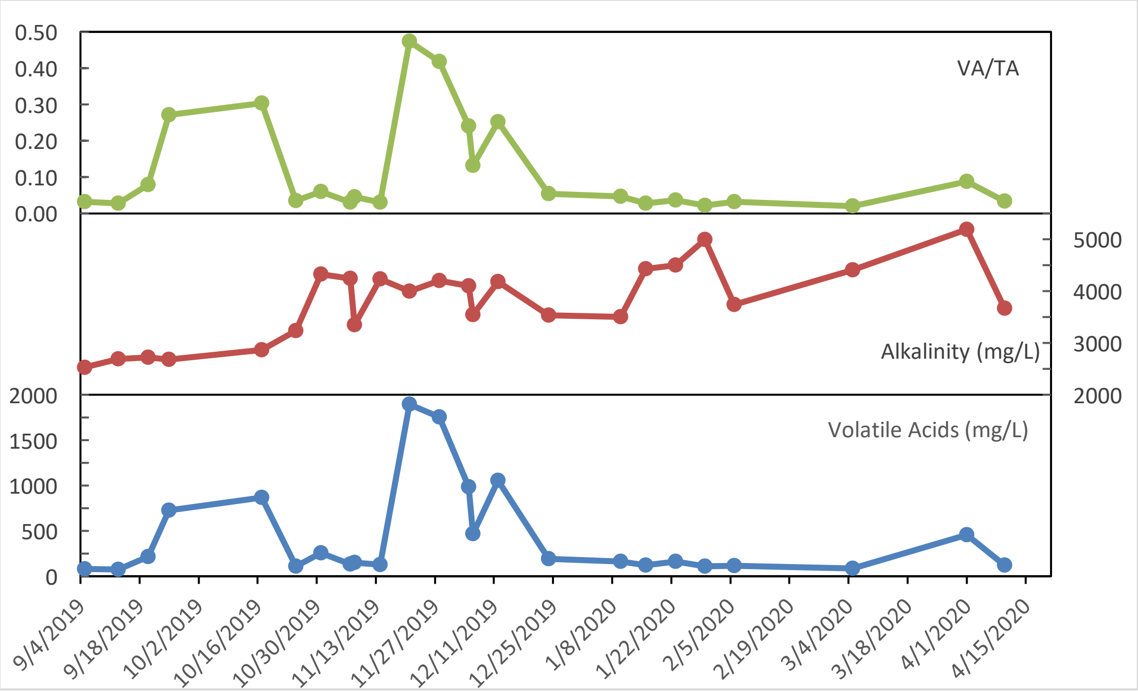
Figure 30 shows the VA and TA for Digester 1 were within acceptable ranges. For Digester 2, Figure 31 shows a sharp increase in VA after November 13, 2020, with a commensurate increase in the VA/TA ratio above the 0.4 threshold. To prevent a digester failure, corrective action was taken by immediately reducing feed rates to Digester 2, which allowed VA levels in Digester 2 to return to normal levels.

Figure 30: Digester 1 Total Alkalinity, Volatile Acids, VA/TA ratio



Source: Lystek International

Figure 31: Digester 2 Total Alkalinity, Volatile Acids, VA/TA ratio



Source: Lystek International

In this demonstration, the target volumetric COD rate 7.5 kg COD/m^3/day. In a study with a similar feedstock[24], the authors reported digester failure at volumetric COD rates greater than 3.5 kg COD/m^3/d, lower than the project target. At 3.5 kg COD/m^3/day, the reported reactor overload was indicated not only by an average VA concentration of 2,288 mg/L, but more importantly a >40% drop in methane yield to around 200 mL/g VS.

In this demonstration, the maximum volumetric rate achieved was 3.33 kg COD/m^3/d, occurred in the week of October 22, 2019. Although this volumetric COD rate was only slightly lower than the reported failure point above, the test digesters showed no indications of imminent failure. The corresponding VA concentration in Digesters 1 and 2 were 383 mg/L and 258 mg/L, respectively. Rather than close to failing, low VA concentrations, and high biodegradability and methane production as shown in December, indicated the digesters were operating below capacity and suggested there was room to increase loading rates.

Throughout the program pH values were relatively stable, usually ranging between pH 7.15 – 7.5, which is within the generally accepted range[20]. A plot of pH readings over the program is presented in Appendix D.

In food waste digestion, ammonia must also be monitored to prevent digester failure. Food waste contains more TN than municipal sludge, which results in higher ammonia levels during FW digestion. Ammonia becomes inhibitory to un-acclimatized cultures at concentrations

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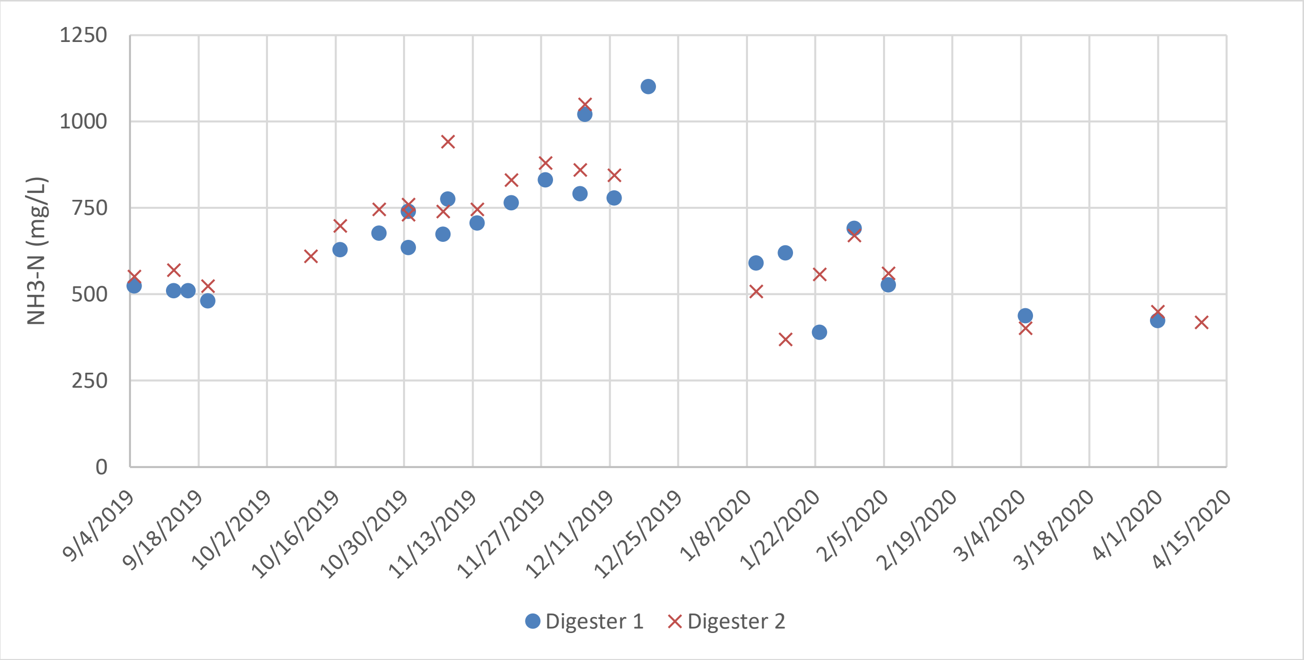
[24] Hegde, S., Trabold, T.A. (2019) Anaerobic Digestion of Food Waste with Unconventional Co-Substrates for Stable Biogas Production at High Organic Loading Rates, Sustainability, 11, 3875, 2019

greater than 1,700 mg/L[25], although with adaptation, inhibition thresholds increase to as high as 15000 mg/L. Digester ammonia levels over the course of the project are shown in Figure 32 which shows the ammonia concentration gradually increasing, as expected, as feeding rates were ramped up. Ammonia peaked above 1,000 mg/L but never exceeded the threshold for inhibition. Following the return to food waste processing and decreased loading rates, ammonia levels fluctuated slightly but then stabilized below 500 mg/L.

Figure 32: Ammonia Levels in Digesters



Source: Lystek International

Summary and Recommendations

Feedstock and COD Loading

1. Four feedstocks were used during the program. Two UCSB dining hall sources, GSD TWAS spiked with sugar, and SSO from a local restaurant. The variable feedstocks were a result of university dining hall scheduling and closures, operational adjustments, and the global COVID-19 pandemic.
2. Program ramp-up was significantly impacted by regular pump blockages, due to large bone and cartilage particles present in the SSO source. These particles were able to pass through the preprocessing system.

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[25] Chen, Y.; Cheng, J.J.; Creamer, K.S. Inhibition of anaerobic digestion process: A review. *Bioresource Technology*, 2008, 99, 4044–4064

3. Difficulty and delays associated with feedstock sourcing and preprocessing resulted in challenges maintaining the volumetric COD loading rate. This, along with the feedstock variability noted above, prevented the program from reaching its design loading rate.
4. Feedstock variability and the lack of real-time availability of test results for COD results contributed to the difficulty in maintaining volumetric COD rates. COD varied by 23% across all SSO sources, and between 19% – 21% within sources.
5. Peak volumetric COD loading was 3.33 kg COD/m^3/d.

Biogas Production

1. Maximum observed biogas production was 28.9 m^3/d. On a 7-day rolling basis, the maximum production rate was 20.3 m^3/d.
2. Biogas yield from SSO was greater than for a mixture of municipal sludge and table sugar. Digestion of the for De La Guerra FW yielded 0.55 m^3 biogas/kg COD fed, vs digestion of the TWAS+sugar, which yielded 0.53 m^3/kg COD.
3. On a per kg VS fed basis, the biogas yield for the De La Guerra SSO was 0.82 m^3/kg VS fed. As expected, this was greater than the yield for GSD, which was 0.60 m3/kg VS fed. This represented an increase of 45%, which exceeded the project objective of increasing biogas production by 30%.
4. Methane content ranged between 56 – 70% and averaged 62.2 ± 3.7% over the program.
5. H_2S content in the biogas ranged from 10 parts per million (ppm) to 200 ppm. Peak levels were associated with SSO from De La Guerra. H_2S was controlled by addition of $FeCl_2$.

Digester Health

1. VA ranged between 45 – 984 mg/L in Digester 1 and 75 – 1894 mg/L in digester two. VA/TA never exceeded 0.4 in digester one. VA/TA in Digester 2 showed a peak at 0.47, indicating an imbalance and warning of a failure. VA/TA was subsequently decreased to below 0.4 as a result of immediately reducing the feeding rate.
2. The pH ranged between 7.0 – 7.5, which is an acceptable target range.
3. Ammonia concentrations rose with increased COD loading, but did not exceed 1100 mg/L.

Based on the experience with this demonstration, the most critical parameter in achieving and maintaining good digester performance is stable and consistent loading. Specific to the lessons from this plant, this means having effective SSO receiving and handling infrastructure and ensuring the plant design includes a robust and effective preprocessing system.

SSO management is important because food waste slurry degrades quickly, especially in warm temperatures. The scale of this demonstration limited SSO receiving (and therefore preprocessing) to weekly deliveries. Although the effect of aged slurry was not discernable in these results, it is likely this factor could impact performance.

In addition to the pulping process, preprocessing should include a size reduction mechanism to help improve digester kinetics and must include a grit removal system to ensure steady hydraulic flow.

Furthermore, where SSO feedstock shows a high degree of variability in COD content, having the capability for rapid on-site COD analysis would be highly advantageous. Regular feed COD monitoring would allow for operational adjustments to be made on a proactive basis to help optimize digester performance.

CHAPTER 6:
Thermal-Alkaline Hydrolysis of Source-Separated Organics

Testing Approach

As described in Chapter 5, the restaurant SSO provided very low biogas yields. Combined with visual observations of the SSO content, it was presumed the low biogas production was due to poor degradability of the FW. Thus, it was decided that after preprocessing, the SSO should be processed through the Lystek THP system to assess its impact on digestion performance.

SSO slurry was processed using Lystek THP at conventional operating conditions (pH, temperature, shear rate) and then fed to Digester 2 on a daily basis at the specific COD loading rate used while digesting the restaurant SSO. To mitigate the uncertainty of feedstock availability due to the COVID-19 pandemic and run the trial for as long as possible by conserving feedstock, only one digester was used for the trial. Two loads of SSO were received, preprocessed, and then processed in the Lystek THP system.

Digester influent and effluent samples were collected and assayed for the same parameters as during SSO digestion, with biogas data being recorded in real time by the plant SCADA system. The pH and H_2S measurements were performed manually by the operators on site.

Results and Discussion

Feedstock Characteristics

Table 9 shows the TS, VS, and total and soluble COD for the two batches of Lystek THP product fed to the digester in this trial, along with the restaurant SSO for comparison.

Table 9: COD, Soluble COD, Total Solids, and Volatile Solids of the Thermal Hydrolysis Process Product

Sample ID	COD (g/L)	sCOD (g/L)	% Soluble COD	TS (g/kg)	%TS	VS (g/kg)	VS (% of TS)
Restaurant SSO	105.0	15.3	15%	40	4%	37	93.0%
Lystek THP Product #1	151.4	35.8	24%	60	6%	51	85.7%
Lystek THP Product #2	123.0	34.0	28%	79	8%	64	81.0%

Source: Lystek International

Another important quality of the Lystek THP product was that, although unmeasured, there was an obvious reduction in particle size that occurred during processing. This was confirmed visually by passing the same volume of the pre-THP and post-THP materials through a 5 mm screen. Figure 33 shows a series of photos of the pre-THP slurry being poured and then accumulating on the screen. In Figure 34, the post-THP product passed easily through the screen. The Lystek THP process resulted in a more homogeneous material after processing.

Figure 33: Pre-Thermal Hydrolysis Process Material Screening

Source: Lystek International

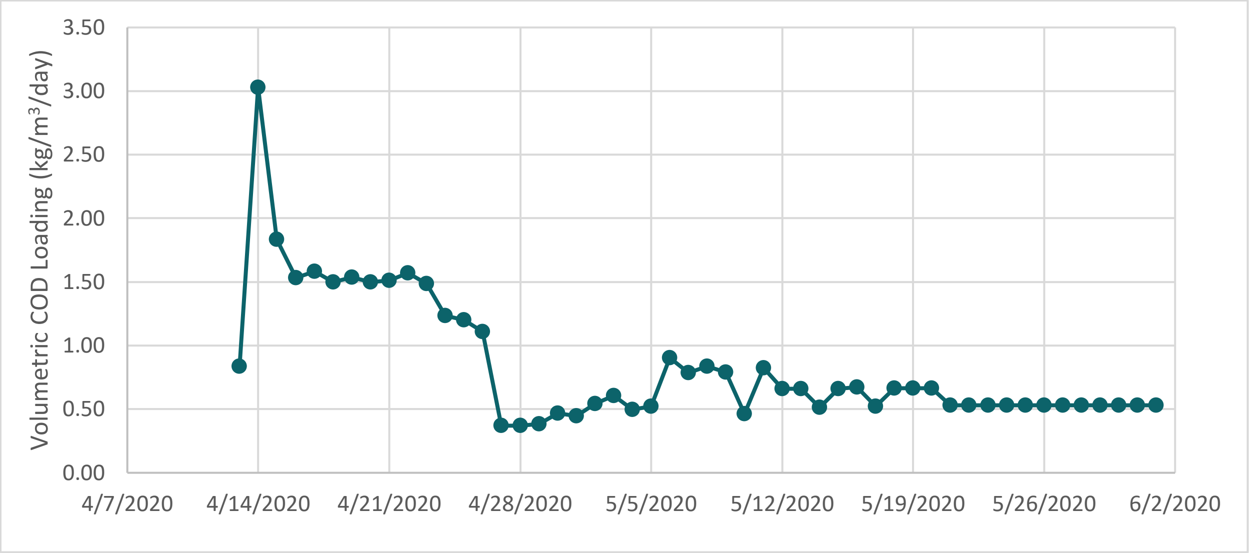
Figure 34: Post-Thermal Hydrolysis Process Material Screening

Source: Lystek International

Volumetric COD Loading Rate

Figure 35 presents the volumetric COD loading rate for Digester 2.

Figure 35: Volumetric COD Loading Rate (Thermal Hydrolysis Process Testing Phase)



Source: Lystek International

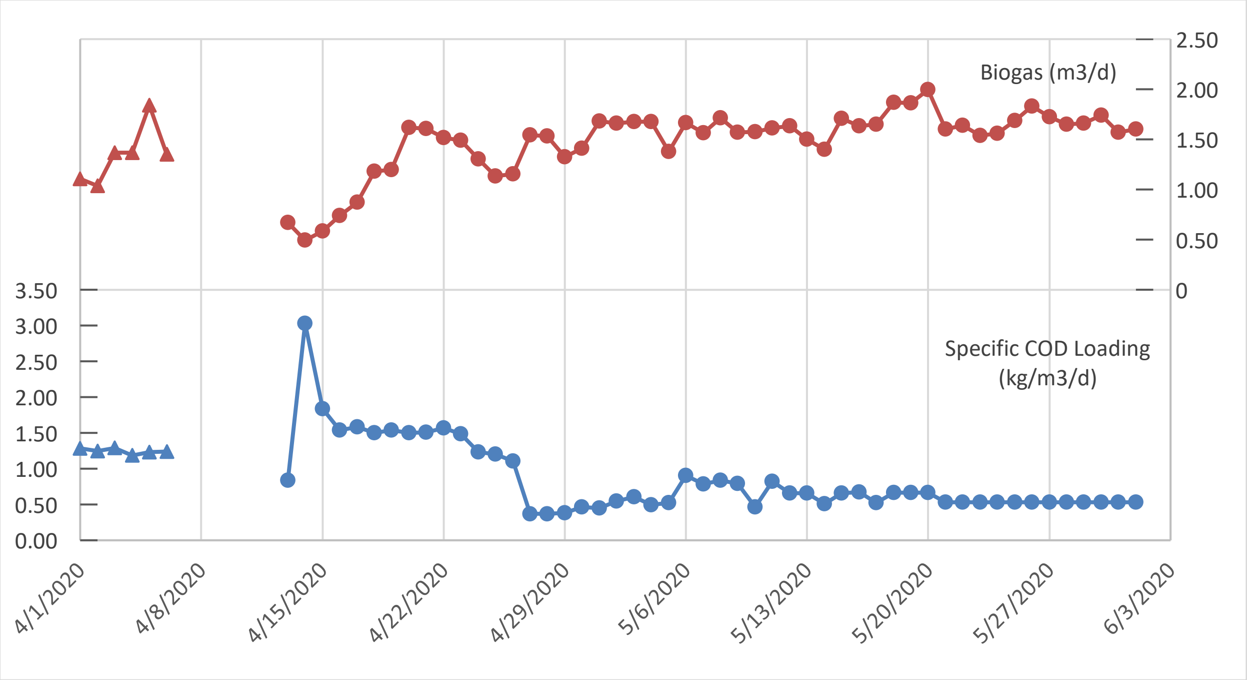
Volumetric COD loading ranged from 0.37 kg/m^3/d to 3.02 kg/m^3/d. The variability in loading during the first two days was due to automation challenges related to digester feed pumping. The initial target was specific loading of 1.25 kg COD/m^3/d to match the restaurant loading. However, due to the time lag in analyzing results, COD loading was slightly higher for the first 10 days than expected and averaged 1.53 kg COD/m^3/d from April 16 to April 23, 2020. Following that, volumetric COD rates were reduced. This was done for two reasons: first to ensure that the digester cultures were completely acclimated to the new feedstock; second to extend the operating period, given the limited and unpredictable availability of feedstock.

Biogas Production

Figure 36 presents biogas production and volumetric COD loading for both Lystek THP product and Restaurant SSO digestion. The figure illustrates that following a short acclimatization period, biogas production averaged 1.58 ± 0.18 m3/d over the trial, 18% higher than the average of 1.34 ± 0.34 m3/d during restaurant SSO digestion. The chart also shows that the higher biogas rate occurred at lower specific COD loading, suggesting better conversion.

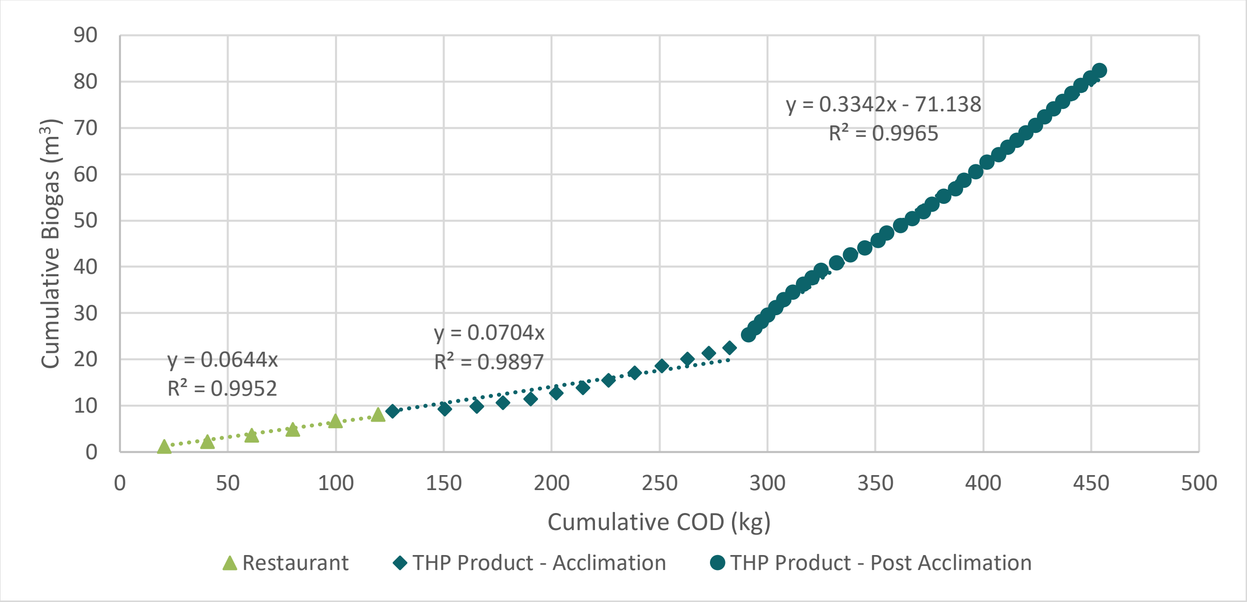
Figure 37 presents the cumulative biogas vs cumulative COD fed to Digester 2 for the Restaurant SSO and Lystek THP product. From the curves a trend line can be plotted to calculate the biogas yield for each feedstock.

Figure 36: Biogas Production and Specific COD Loading Rate (Thermal Hydrolysis Process Testing Phase)



Source: Lystek International

Figure 37: Cumulative Biogas versus Cumulative COD, (Restaurant SSO and Thermal Hydrolysis Process Testing)

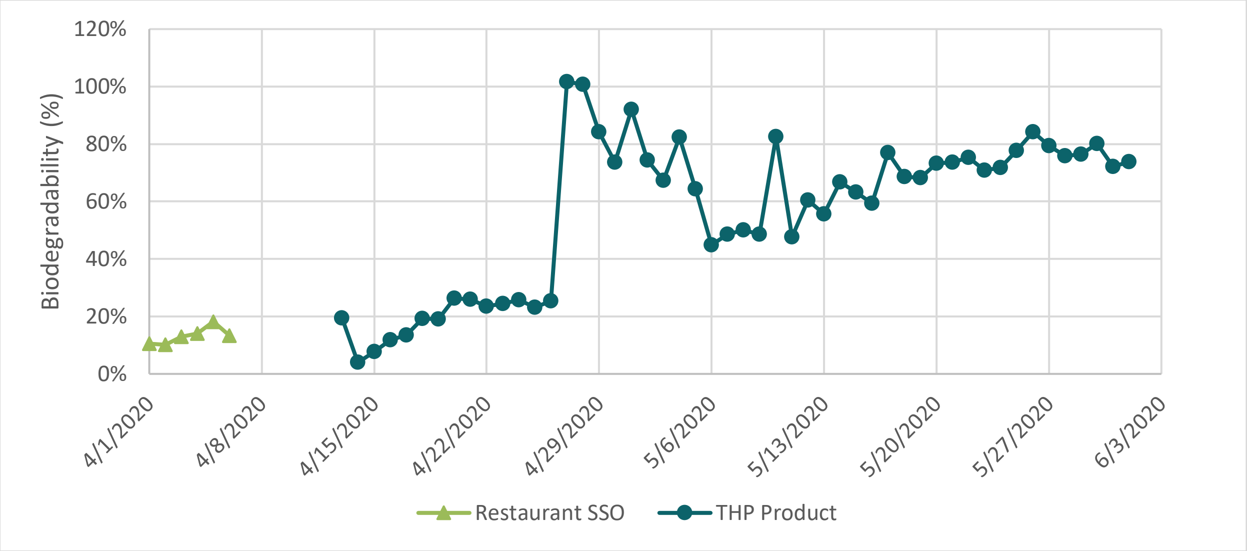


Source: Lystek International

The Lystek THP product data is broken into two distinct stages, representing the acclimation and post-acclimation periods for the new feedstock. In Figure 37 the trend lines show that during the THP-acclimatization period the biogas yield was similar to that achieved during digestion of the Restaurant SSO. However, after the culture became acclimatized to the new feedstock, the biogas yield increased by a factor of 4.7, from 0.07 $m^3/kgCOD_{fed}$ to 0.33 $m^3/kgCOD_{fed}$.

Figure 38 presents feedstock biodegradability during the thermal hydrolysis testing phase.

Figure 38: Biodegradability (Thermal Hydrolysis Process Testing Phase)



Source: Lystek International

Comparing biodegradability from digestion of the restaurant SSO to digestion of the Lystek THP product, the restaurant SSO yield peaks at 18%, while the THP product peaks above 100% and has five days of biogas yields above 80%. At the introduction of the Lystek THP product, degradability was as low as 4%, but increased immediately during the acclimatization period. During that period there was a steady upward trend in biodegradability from 4% to 26% and then a plateau between April 20 to April 26. After April 27, there is a large jump that corresponded in time with decreased volumetric COD loading. It is possible this was due to further hydrolysis, acidogenesis, and methanogenesis of the (relatively) large volume THP product fed initially, specifically the microbes were able to work through a "backlog" of feed while further acclimatizing. Following a drop from the high point, the chart shows the biodegradability steadily increasing during the remainder of the trial. In the last week of the trial, the average was 77.4% ± 3.8%.

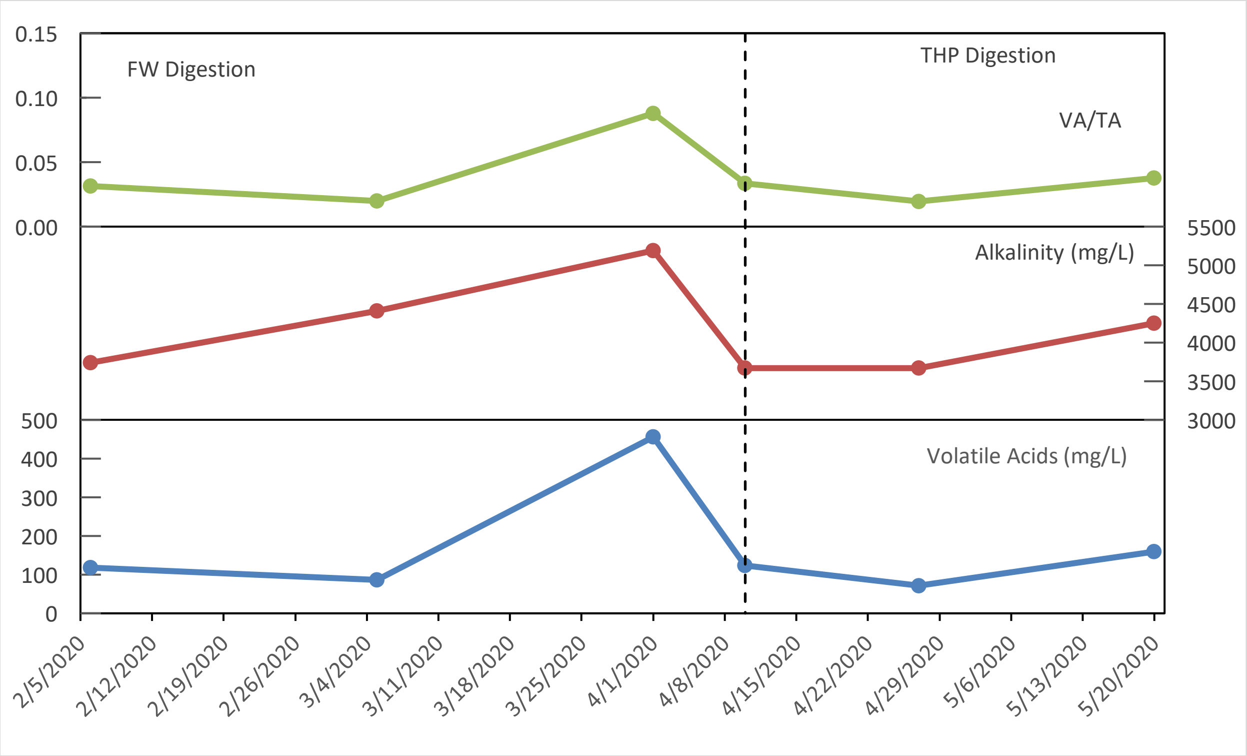
Taken together, the data indicate that once the culture is acclimatized to the Lystek THP product as its feedstock, digester performance, specifically biogas generation, is substantially improved. The results demonstrate that more biogas could be produced at lower volumetric COD loadings. For the period April 27 to June 2, biogas production from the THP product was 21% higher (1.63 ± 0.13 m^3/d) than for the restaurant SSO (1.34 ± 0.34 m^3/d). Additionally, volumetric COD loading of the THP product was 53.5% lower compared to the restaurant SSO. These data indicate the biodegradability of the THP material was 2.6 times higher than the restaurant waste.

These results are supported by an independent lab-scale batch BMP test conducted by Dr. Nakhla at Western University (Appendix F). The extensive BMP tests were designed to compare the biogas production of the untreated restaurant SSO and Lystek THP treated SSO at low and high loading rates, with acclimatized (from the GSD digesters) and unacclimatized (from the Strathroy, Ontario, municipal WWTP) anaerobic biomass. The study concluded that: the SSO was not readily biodegradable and potentially inhibitory, with biodegradation efficiency of only 40% – 60% at very low loadings (< 0.3 kg COD/m^3-d) decreasing to only 12% at 3.2 kg COD/m^3-d; and, Lystek THP processing improved biodegradability and biogas yields by 40%-60% at loadings greater than 0.3 kg COD/m^3-d.

Volatile Acids, Total Alkalinity, and Digester Stability

Another interesting result can be gleaned from comparing VA, TA, and VA/TA ratios during the food waste digestion and Lystek THP product digestion. The data are plotted in Figure 39.

Figure 39: Digester Volatile Acids, Total Alkalinity, and VA/TA Ratio (Lystek Thermal Hydrolysis Process Testing Phase)



Source: Lystek International

The VA/TA ratio is a good indicator of the stability of digester operations. During the second seeding of the FW digestion trial (March 3, 2020 – May 20, 2020), the VA/TA ratio on average was 0.046 ± 0.03, indicating a high degree of variability (ratio of standard deviation to average or relative standard deviation of 65%). By contrast, Lystek THP product digestion proved more stable, with an average VA/TA ratio of 0.030 ± 0.008. It must be asserted however, that although the VA/TA ratios for the FW reflect no accumulation of VA, the accumulation of VA resulting in high VA/TA is an indication of the inhibition of methanogens. The low biodegradability of the FW was not attributable to inhibition of methanogens but to the inhibition of fermentative bacteria that are responsible for hydrolysis and acidogenesis.

Summary

During the trial of Lystek THP product digestion, digester performance was measured by biogas production. Digester health was monitored by measuring the concentrations of VA, TA, and ammonia. The main findings for the program are as follows:

1. Lystek THP processing resulted in a substantial reduction in particle size and reduced feedstock viscosity.
2. After an initial acclimation period, the digester gas production was 21% higher with the Lystek THP product than from the restaurant SSO.
3. With the Lystek THP product, more gas was produced from less COD fed to the digester. Biogas yields increased from 0.06 $m^3/kgCOD_{fed}$ during restaurant SSO digestion to 0.33 $m^3/kgCOD_{fed}$ during THP product digestion.
4. Lystek THP product digestion showed lower variability in the VA/TA ratios compared to FW SSO digestion, indicating that THP product digestion was a more stable process.

This combination of pre-treatment by thermal hydrolysis and AD showed that increased biogas yields from food and organic wastes could be obtained, demonstrating a technical advancement that could be used to help the state meet its energy goals by broadening the types and quantities of organic feedstocks available for biogas generation.

CHAPTER 7:
Projected Benefits and Economic Evaluation

Economic Analysis for an Illustrative Wastewater Treatment Plant

In a report released by the California State Water Resources Control Board, Carollo Engineers[26] analyzed the state's capacity for diverting organic waste from landfills by co-digestion. In this analysis, the authors presented an illustrative case for the economics of a medium-sized WWTP receiving organic waste for co-digestion, with biogas end use split 95:5 between compressed natural gas (CNG) vehicle fueling and site use. To analyze the economic and GHG benefits of FW-only digestion, the methodology and base case parameters (for example, feedstock volume and composition) from the report's analysis were used with operating results from this demonstration.

For the illustrative case presented here, the same assumptions were made: the WWTP had sufficient excess (out-of-service unit) AD capacity to digest 45,000 short wet tons of FW slurry received at 30% TS (referred as "wet tons"), but that it lacked the additional infrastructure required to receive the FW, dewater the additional digestate, and make beneficial use of the additional biogas. For the analysis, the operational parameters are summarized in Table 10.

Table 10: Parameters Used for Economic Calculations

Parameter (Units)	Co-digestion	FW-Only Digestion
Total Solids (%)	30%	30%
Volatile Solids (% of VS)	86%	86%
Biogas Yield (SCF/lb TS_{fed})	11	N/A
Biogas Yield (SCF/lb VS_{in})	N/A	13.2*
Biomethane Content (%)	60	62*
Biomethane Yield (SCF/lb VS_{in})	7.7	8.2
VSR (%)	75	86*

Notes: * denotes data derived from program results

Source: Lystek International

In the co-digestion analysis, the authors derived the methane yield on a per TS basis. Because the biogas (and hence methane) yields presented in Chapter 6 were derived on a per VS basis,

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[26] Carollo (2019) Co-digestion Capacity in California. Retrieved from: https://www.waterboards.ca.gov/water_issues/programs/climate/docs/co_digestion/final_co_digestion_capacity_in_california_report_only.pdf

the biomethane yield from the report was converted to the same basis to ensure an equivalent comparison.

Capital costs for the scenario were estimated in the report from either known costs or by using unit factors reported in the literature. In the report, net costs associated with multiple scenarios (electricity only, vehicle CNG only, and even splits between electricity, vehicle CNG, and pipeline CNG) were presented, while a detailed breakdown of costs was presented for the electricity/vehicle CNG scenario only.

This analysis considered electricity generation only. To ensure reproducibility of the co-digestion methodology, the economics for electricity via co-digestion were recalculated and compared against the report findings. Detailed results of the capital and operations and maintenance (O&M) amounts for the co-digestion case are tabulated in Appendix D.

Capital costs and operating costs were taken directly from the report. An internal combustion cogeneration unit was assumed for electricity production. The co-digestion report did not specify cogeneration type. In this analysis, net cost was calculated to be $11 per wet ton, which compares favorably with the $10 per wet ton cost reported previously.

In the co-digestion analysis, the authors did not apply RIN credits to the economic analysis. The US EPA[27] indicates that renewable electricity generated from waste digester biogas (Pathway T) is eligible for RIN credits in the D5 bucket, while renewable electricity derived from AD of the FW fraction of municipal solid waste (MSW) is eligible for D3 credits via Pathway Q. Including revenue associated with the sale of D5 RIN credits (trading at roughly $0.50/credit at the time of writing), the total cost would decrease to $4/wet ton.

The same method was then applied to evaluate the economics for the FW-only digestion scenario based on the results achieved during the project. Detailed results for capital and O&M costs are presented in Appendix D.

Including revenue associated with the sale of D5 RIN credits plant economics become favorable with a net revenue of $6 per wet short ton food waste at 30% solids. With D3 eligible credits ($1.50/credit at time of writing), the net revenue becomes $23 per wet short ton food waste at 30% solids. Clearly, revenue from RIN credits would be a significant driver in the economics of the facility. However, a lack of clarity around RIN eligibility and future prices could be a disincentive for WWTPs to take on the additional operational risks of processing diverted FW. Detailed results of the capital and O&M amounts for the co-digestion case are tabulated in Appendix D.

However, based on the biogas yield and VSR observed during the FW demonstration, FW-only digestion of organic waste can realize other potential savings. Most notably, increased VSR associated with FW-only digestion results in fewer dry solids to be dewatered and hauled off-site. In this illustrative case, decreased residuals reduced operations and maintenance (O&M) costs by roughly $325,000. In a scenario where RIN credits were unavailable, the savings in O&M would be insufficient for the illustrative plant to generate a profit, but did improve the

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[27] USEPA, (2021). Approved Pathways for Renewable Fuel. Retrieved from https://www.epa.gov/renewable-fuel-standard-program/approved-pathways-renewable-fuel.

net cost enough (to a loss of $2 per wet short ton) to suggest that the economics might be favorable with higher tipping fees and/or electricity prices. Indeed, the results of a sensitivity analysis (Table 11) show that increases in either tipping fees or electricity rates alone can make the process revenue positive.

Table 11: Total Plant Cost Sensitivity Analysis

Electricity Price ($/kWh)	Tipping Fee ($/wet ton)					
	10	15	20	25	30	40
0.04	-$37	-$27	-$17	-$7	$3	$23
0.06	-$29	-$19	-$9	$1	$11	$31
0.08	-$22	-$12	-$2	$8	$18	$38
0.10	-$14	-$4	$6	$16	$26	$46
0.12	-$7	$3	$13	$23	$33	$53
0.14	$0	$10	$20	$30	$40	$60

Source: Lystek International

Greenhouse Gas Emission Reductions

The analysis to determine the GHG emission reductions due to digestion of diverted food waste follows the method outlined in the co-digestion report. In the report, the authors compared co-digestion to landfilling food waste. An emissions reduction factor (ERF) was calculated for FW-only digestion from the following equation:

$$\text{FWERF} = (\text{ALF} + \text{BGE} + \text{DLA}) - (\text{TE} + \text{PE})$$

Where,

- FWERF = FW digestion emission reduction factor
- ALF = Emission reduction associated with the avoidance of landfill methane emissions
- BGE = Emission reduction associated with the use biogas used to generate electricity
- DLA = Emission reduction associated with digestate land application
- TE = Transportation emissions
- PE = Process emissions

All units for the emissions factors are metric ton CO_2 equivalent per short wet ton diverted food waste at 30% solids ($MTCO_{2e}$/wet ton). Similar to co-digestion, the main emissions associated with FW-only digestion are transporting and preprocessing the diverted food waste, digester heating, and dewatering the digestate. Transportation and process emissions factors were estimated using the same transportation distances and unit operation energy consumption rates presented in the co-digestion study. Transportation emissions will depend heavily on the local geography. CARB estimated a transportation emission factor of 101 g CO_{2e}/ton-mile. Table 12 summarizes the transportation distances and emissions factor.

Table 12: Transportation Emissions Factor

Weighted Average Transportation	Miles	Conversion Factor	Total (Ton-miles)
30% TS Food Waste to MRF	11.6	1	11.6
15% TS Slurry to WWTP	11.6	2	23.2
Digestate	116.2	0.290	33.8
Total			68.6
TE			0.0069

Source: Lystek International

Process emissions are summarized in Table 13.

Table 13: Process Emissions Factor

Process Emission Source	Unit Input	Emission Factor	PE Factor
Preprocessing	30 kWh	0.228 kg CO_2e/kWh	0.0068
Digester Heating	0.125 MMBTU	52.338 kg CO_2e/MMBTU	0.0065
Dewatering	3.92 kWh	0.228 kg CO_2e/kWh	0.0009
Polymer Production	1.49 lbs	1.26 kg CO_2e/lb	0.0019
Polymer Delivery	1.49 lbs	1.52 kg CO_2e/lb	0.0002
PE			0.0164

Source: Lystek International

Emissions reductions due to FW-only digestion result from the avoided landfill emissions, use of digestate for land application, and beneficial use of biogas to displace fossil sources of energy. For this analysis, the same ALF factor was used as in the co-digestion study, 0.388 $MTCO_{2e}$/wet ton. The digestate land application (DLA) factor was recalculated, due to the reduction in solids leaving the facility relative to the incoming wet tonnage, at 0.04 $MTCO_{2e}$/wet ton. Lastly, an emissions factor for beneficial use of the biogas was determined from CARB's CCI Emission Factor database. In the co-digestion study, the authors calculated an ERF for renewable electricity generation with the biosolids composted based on the average of small-medium and medium-large facilities WWTP, yielding an ERF of 0.21 $MTCO_{2e}$/wet ton. In this analysis, the ERF for electricity generation for stand-alone AD with land applied digestate, 0.21 $MTCO_{2e}$/wet ton, was used. To reflect the use of land-applied codigested biosolids, the BioG term for co-digestion was changed from 0.21 $MTCO_{2e}$/wet ton (compost end-use) to 0.19 $MTCO_{2e}$/wet ton. The ERFs for each case are summarized in Table 14.

Table 14: Emission Reduction Factors

Emission Reduction Type	Emission Reduction Factor	
	Food Waste	Co-digestion
Avoided Landfill Emissions – ALF	0.388	0.388
Digestate Land Application – DLA	0.04	0.055
Biogas Use - Electricity/Land App - BGE	0.21	0.19
Net Emission Reduction Factor	0.64	0.63

Source: Lystek International

In the comparison of co-digestion vs landfill, the process and transportation terms were set to zero since they were roughly equivalent for each case. To maintain consistency in comparing co-digestion to FW-only, they have been excluded on the same basis.

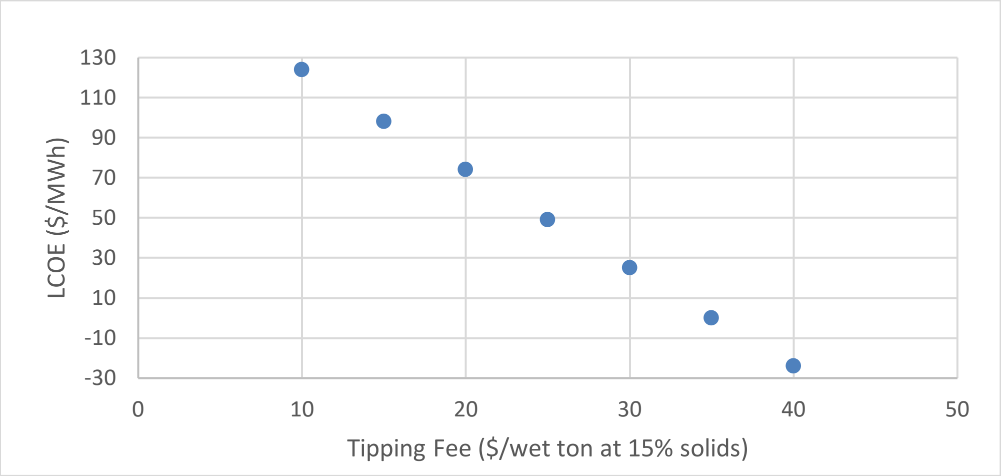
The total potential emission reductions for food waste only and co-digestion are 28,740 $MTCO_{2e}$ and 28,485 $MTCO_{2e}$., respectively. This represents a further reduction in GHG emissions of approximately 255 $MTCO_{2e}$ when FW-only digestion is used over co-digestion.

Levelized Cost of Electricity

To determine the Levelized Cost of Electricity (LCOE) for electricity from food waste only digestion, the SB1122 LCOE Calculator was used, based on the data used in the Illustrative Case. For the model, the technology selected was "Food Waste" and the Cost Scenario was "Low". User modifications were input to the "Technical Entries" section to reflect the conditions and costs in the Illustrative case. The "Financial Entries" and "Incentives" sections were left unmodified. The inputs for the LCOE and Energy Fuel Cost Calculator are detailed in Appendix D.

The LCOE for the conditions analyzed was $74/MWh. THE LCOE electricity represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant during an assumed financial life and duty cycle. In the case of the WWTP described above, were such a facility to be newly constructed for the purpose of generating electricity, it would require revenue of $0.74/kWh, which would mean rates in excess of what ratepayers currently pay. However, while running the model, it was noticed that the tipping fee had a large bearing on LCOE. Figure 40 illustrates the LCOE vs tipping fee, and shows that as the tipping fee increases, the LCOE for the Illustrative Case decreases.

Figure 40: Levelized Cost of Energy Sensitivity Analysis



Source: Lystek International

Because such a plant would have the ability to set a tipping fee for the organic waste it receives, the tipping fee can be used as a lever to reduce the LCOE and improve plant economics. The sensitivity analysis showed that once the tipping fee exceeds $35 per wet ton, the revenue from electricity generation is no longer the major economic driver for the plant. In 2015[28], the median cost of disposing MSW (which contains food waste) via landfill in California was $45 per ton, which would make new construction for electricity generation from AD of food wastes economically feasible.

Benefits to California Ratepayers

According to the co-digestion report, should WWTPs use their existing largest out-of-service units for food waste only digestion, there is sufficient AD capacity to process up to 2,400,000 short wet tons of diverted organic[29]. This would increase the benefits that could be gained by co-digestion.

Increased Energy Recovery

The estimated amount of energy that could be produced from co-digestion of the 2,400,000 short wet tons is roughly 113 MW. Using FW only digestion could result in up to 120 MW of power production, an increase of 6%, or 7 MW total.

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[28] CalRecycle, (2015). Landfill Tipping Fees in California. Retrieved from: https://www2.calrecycle.ca.gov/Publications/Details/1520

[29] Carollo (2019) Co-digestion Capacity in California. Retrieved from: https://www.waterboards.ca.gov/water_issues/programs/climate/docs/co_digestion/final_co_digestion_capacity_in_california_report_only.pdf

Reduced Greenhouse Gas Emissions

As in the case of energy generation, FW-digestion has the potential to create further GHG emission reductions. In California, the additional GHGs avoided could be up to 13,600 $MTCO_{2e}$.

Revenue Generation for Wastewater Treatment Plants

The economic analysis above showed that there is potential for WWTPs in California to generate revenue by receiving diverted organic waste and generating electricity with the produced biogas. The amount of revenue generated will vary for each WWTP, and will depend on plant scale, tipping fees, energy prices, and renewable energy credit availability. As public utilities, this value could be returned to rate payers resulting in a net benefit to them.

Summary

Based on the operational and performance data collected during the food waste digestion trial, an illustrative case was developed for electricity generation at a WWTP receiving and digesting 45,000 wet tons/year of diverted food waste. In the case, the economics and GHG reduction potential of such an operation were evaluated and compared to an identical facility processing the same volume of diverted food waste by co-digestion. Plant economics were evaluated with and without the application of RIN credits.

In the co-digestion case without any RIN eligibility, the total cost was $11/wet ton. In the food waste only digestion case without RIN eligibility, total cost was $2/wet ton. The reduction in total costs was due to the increased biogas production and decreased digestate processing and management costs associated with FW-only digestion. When D5 and D3 RIN credits are applied to the co-digestion and FW-only cases, respectively, the total cost for the co-digestion scenario becomes $2/wet ton, while the FW-only scenario becomes profitable at a revenue of $23/wet ton.

Additionally, a sensitivity analysis was conducted to determine the impact of electricity price and tipping fee on plant economics. The analysis showed that for food waste only digestion, an increase in either tipping fee or electricity price from the base assumptions ($20/wet ton and 0.08 $/kWh, respectively) food waste digestion becomes a revenue positive service.

With respect to GHG reduction potential, the impact of co-digestion and FW-only digestion are roughly the same. In the cases analyzed, between 28,485 $MTCO_{2e}$ and 28,740 $MTCO_{2e}$ emissions could potentially be avoided.

Lastly, the LCOE was calculated for the 45,000 wet-ton/year FW-only digestion case. At a tipping fee of $20/wet ton, the LCOE was calculated at $74/MWh. A sensitivity analysis showed the LCOE decreased linearly with tipping fee, indicating economic feasibility and lower electricity rates are possible with high enough tipping fees.

CHAPTER 8:
Production Readiness Plan

The project demonstrated that after preprocessing with a mature depackaging technology, food waste digestion can be used to successfully transform source-separated organics into a valuable fuel. The depackaging technology met its manufacturer's claims that SSO could be processed with the resulting slurry containing <1% contamination by mass. By the difficulties in operation, the project also demonstrated that well-slurried SSO is not enough to ensure reliable operations: additional preprocessing steps to remove organic contaminants and polish the slurry are also required.

Lastly, when faced with potentially inhibitory food waste, the project demonstrated that pretreating the digester feed via Lystek Thermal Hydrolysis can improve the biodegradability of a recalcitrant feed up to 2.6 times.

All technologies have been demonstrated and used in full-scale plants. If a WWTP operator wishes to bring an existing, out-of-service digester online for food waste digestion, these technologies can be readily installed and operated with minimal modifications needed for any site-specific requirements.

CHAPTER 9:
Summary and Conclusions

This project successfully demonstrated that a containerized depackaging system could be used to preprocess source-separated organic waste into a slurry suitable for AD and conversion to biogas. The following specific objectives were achieved:

1. Produce +99% contaminate free digester feedstock from SSO by preprocessing with a new depackaging technology.
2. The organic slurry produced in the preprocessing step was digested via AD, and converted into biogas.
3. Lystek THP treatment of difficult-to-degrade food waste can substantially increase VS breakdown resulting in increased biogas yield from FW.

Key Conclusions

This section details results of the main objectives.

1. The preprocessing unit produced an organic slurry with <0.1% contamination on a wet-weight basis, and <0.5% on a dry-weight basis.
    a. While the unit successfully removed inorganic contaminants, we stress that preprocessing technology selection is critical for effective operations. In this case, the selected unit was unable to process the garbage bags that contained the SSO, necessitating operator intervention upstream of the unit.
2. AD of FW resulted in greater unit gas production and VSR than municipal sludge-only digestion at GSD.
    a. Maximum observed biogas production was 28.9 m^3/d. On a 7-day rolling basis, the maximum production rate was 20.3 m^3/d.
    b. Methane content ranged between 56 – 70% and averaged 62.2 ± 3.7% over the program.
    c. Biogas yield from SSO was greater than from a mixture of municipal sludge and table sugar. Digestion of food waste yielded 0.58 m^3 biogas/kg COD fed versus digestion of the TWAS+sugar, which yielded 0.53 m^3/kg COD.
    d. On a per kg VS fed basis, the biogas yield for SSO was 0.82 m^3 biogas/kg VS_{fed}. This was higher than the yield for digestion of municipal sludge observed at GSD, which was 0.60 m3/kg VS_{fed}. This represents an increase of 45% in biogas production.

    e. H_2S content in the biogas ranged from 10 ppm to 200 ppm. Peak levels were associated with SSO feedstocks that contained high proportions of red meat. H_2S was controlled by addition of $FeCl_2$.

3. Pretreatment of the anaerobic digester feed by thermal hydrolysis increased biogas yields from difficult-to-digest food wastes.
    a. Lystek THP treatment resulted in a substantial reduction in particle size and reduced feedstock viscosity.
    b. After an initial acclimation period, the digester gas production was 21% higher with the Lystek THP product than from the restaurant SSO.
    c. Biogas yields increased 5.5-fold, from 0.06 $m^3/kgCOD_{fed}$ during restaurant SSO digestion to 0.33 $m^3/kgCOD_{fed}$ during THP product digestion.
    d. Lystek THP product digestion showed lower variability in the VA/TA ratios compared to FW SSO digestion, indicating that THP product digestion was a more stable process.

Conclusions from the Economic Evaluation

Based on the data and results considered in Chapter 7, the main results of the economic evaluation include the following.

1. Estimates for the capital expenses of upgrading a WWTP to process 45,000 short wet tons (30% solids) of diverted organics were $21,233,000 for processing via co-digestion and $20,933,000 for FW-only digestion.
2. Estimates for the annual O&M expenses were estimated at $1,750,000 and $1,424,000 for processing and renewable electricity production via co-digestion and FW-only digestion, respectively.
3. Revenue sources included FW tipping fees and renewable electricity sales. Additionally, the applicability of RIN credits strongly influences the revenue. Co-digestion is eligible for D5 credits, while FW-only digestion is eligible for D3 credits.
4. The net cost for the co-digestion scenario was $4/wet ton received, with the inclusion of D5 credits. The net revenue for the FW-only digestion scenario was $6/wet ton received with D5 credits, and $23/wet ton received with D3 credits.
5. Potential emissions reductions for the FW-only AD facility analyzed in the Illustrative Case were calculated to be 28,740 MT CO2e.
6. The LCOE for the FW-digestion only facility was $74/MWh. A sensitivity analysis of the LCOE with respect to food waste tipping fee showed an inversely proportional relationship, and that the LCOE becomes negative at tipping fees greater than $35/wet ton received.

7. These results indicate that FW-only digestion has the potential to be used a source of reliable, lower cost electricity generation in the state of California.

Statewide Benefits Summary

Food waste digestion and co-digestion present tremendous opportunities for California to improve resource recovery, increase sustainable energy production and reduce statewide GHG emissions.

By implementing food waste digestion at WWTPs to process diverted organic waste at the levels in recently enacted legislation (primarily SB-1383), California could realize additional gains in energy recovery and reduced GHG emissions. These gains include increased biogas generation, which can sustainably produce an additional 7 MW of energy annually, and a further reduction in GHG emissions of 13,600 $MTCO_{2e}$ annually. Furthermore, the applicability of higher value D3 RIN credits to FW-only digestion means that WWTPs implementing this strategy could realize added revenue(s), which could have a positive impact on California rate payers.

LIST OF ACRONYMS

Term	Definition
AD	anaerobic digestion
ATC	authority to construct
AWMA	Air and Waste Management Association
BMI	Barnum Mechanical Inc
BMP	biochemical methanation potential
CalOSHA	California Division of Occupational Safety and Health
CASA	California Association of Sanitation Agencies
CEC	California Energy Commission
CEQA	California Environmental Quality Act
CNG	compressed natural gas
COD	chemical oxygen demand
D2O	Design2Operate
EPIC	Electric Program Investment Charge
EPRI	Electric Power Research Institute
ERF	emissions reduction factor
FOG	fats, oil, and grease
FW	food waste
GHG	greenhouse gas
GSD	Goleta Sanitary District
LCOE	levelized cost of electricity
LEA	local enforcement agency
MGD	million gallons per day
MMBTU	million British thermal unit
MSW	municipal solid waste
ND	Negative Declaration
NOD	Notice of Determination
OEC	Oilfield Environmental and Compliance Inc.
OREX	Anaergia’s Organics Extrusion Press
OSP	Athens Services Organic Separation Press
O&M	operations and maintenance
ppm	parts per million
ppmV	part per million by volume

Term	Definition
PTO	permit to operate
RIN	Renewable Identification Number
SBCAPCD	Santa Barbara County Air Pollution Control District
SCADA	supervisory control and data acquisition
SMA	specific methanogen analysis
SSO	source-separated organics
SWRCB	State Water Resource Control Board
TA	total alkalinity
THP	thermal hydrolysis process
TN	Total Nitrogen
TS	total solids
TWAS	thickened waste activated sludge
UCSB	University of California, Santa Barbara
US	United States
US EPA	United States Environmental Protection Agency
VA	volatile acids
VA/TA	volatile acids to total alkalinity
VS	volatile solids
VSR	volatile solids reduction
WRRF	water resource recovery facility
WWTP	wastewater treatment plant

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APPENDIX A:
Design, Contracting and Construction

Overall Approach

During the design and construction of the skids, four parties were involved:

Preprocessing skid

- Smicon BV was contracted for the fabrication, commissioning, and start-up of the SSO preprocessing unit.

Processing skids

- Lystek was the project owner, responsible for overall technical direction, detailed design approvals, and commissioning oversight.
- Design2Operate (D2O) was contracted to provide conceptual skid design, which included piping and instrumentation diagrams, equipment sizing and recommendations.
- Barnum Mechanical Inc (BMI) was contracted for the detailed mechanical and electrical design, procurement, skid fabrication, installation on site, and commissioning activities.

Construction of the Skids

Preprocessing Skid

Design and fabrication were completed in-house at SMICON's location in Wanroij, Netherlands, from January through July 2019. The unit was delivered to GSD in August 2019.

Processing Skids

Design and engineering activities, including CAD design and skid layout, shop drawings, Process & Instrumentation Diagrams (P&IDs), equipment list, as well as electrical and controls design were conducted from February through August 2018. Equipment was procured between June and November 2018. Long-lead items included the Lystek THP Reactor, control panel and agitator, digester tanks, boiler, and flare.

Shop fabrication, including building the skid frames, installing the equipment (reactor, boiler, etc.), connecting piping, electrical and controls installation, and programming, was completed in November 2018. Preliminary testing prior to shipping was conducted at BMI's facilities in December 2018. A California Energy Commission (CEC) delegation visited BMI's shop on February 8, 2019 to observe final configuration and verify completed fabrication of the Lystek mobile skid unit.

Following the CEC visit, the equipment was packed for shipping pending final permits. The unit was delivered at GSD in April 2019. The skids were roughly placed and covered pending the approval of Santa Barbara County Air Pollution Control District's (SBCAPCD) Final Authority to

Construct (ATC) permit. Onsite assembly started on June 3, 2019 and was completed in July 2019. Cold and hot testing took place in August 2019, and the first food waste load was processed on August 27, 2019. Figure A-1 and Figure A-2

and present a selection of construction photos from shop fabrication and site installation, respectively.

Shop Fabrication of the Process Skids

Figure A-1: Shop Fabrication of the Process Skids

Source: Lystek International

Figure A-2: Installation of the Skids at Goleta Sanitary District

Source: Lystek International

APPENDIX B:
Permitting

Overall Permitting Approach

During the preparation of the original EPC-17-022 application, Lystek undertook a review of the potential environmental and operating permits required for this project. Though the project was scaled as a demonstration project, there were components that had the potential to cause measurable emissions or impacts. The team identified the following major areas of concern and the potential oversight agency:

- Air emissions; Santa Barbara County Air Pollution Control District (SBCAPCD)
- Land use impacts; GSD
- Material handling requirements; Local Enforcement Agency (LEA) and CalRecycle
- Health and safety provisions; California Division of Occupational Safety and Health (CalOSHA)

Many of these items are routinely investigated as part of any project review in accordance with the California Environmental Quality Act (CEQA), a California statute passed in 1970 to institute a statewide policy of environmental protection. CEQA does not directly regulate land uses, but requires state and local agencies within their jurisdiction to follow a protocol of analysis and public disclosure of environmental impacts of proposed projects and adopt all feasible measures to mitigate those impacts. CEQA makes environmental protection a mandatory part of every California state and local (public) agency's decision-making process.

The issue of air emissions would be a result of the processing and degradation of organic waste, either by natural means or controlled AD. Anaerobic digestion is the biological process of organic breakdown into its main constituents of methane, carbon dioxide, and water. Air emissions could also result from the un-managed organic waste matter that would be delivered as project feedstock. Additional air emissions would result from the use of a portable generator powered by diesel fuel. Though the project would have access to the available power at the GSD facility, there was a high likelihood that additional power needs would be required beyond the capacity of the GSD plant. The SBCAPCD has prescriptive guidelines for the use of diesel-powered generators and a calculation method to determine other sources of emissions depending on the type of project operations.

Land use impacts were going to be limited due to the nature of the project size at the ability to locate the project equipment within the limits of the GSD property/permit boundary. While the GSD property size is approximately 26 acres, the Lystek proposed project had an estimated project footprint of less than 0.05-of-an-acre (or about 2,000 sq. ft.). Sufficient space was available at the GSD site for the project. In addition, concerns about potential aesthetics due to visual impacts were negated by keeping all project equipment heights below GSD’s existing equipment elevations.

One of the key project components was the delivery, post-processing, and handling of preprocessed organic food wastes to the Lystek project. Lystek identified the University of California, Santa Barbara (UCSB) as a project partner to provide the organic feedstock for pre-processing. UCSB (as well as other UC-system institutions) were looking for projects to reduce their practice of landfilling organic/food materials. While small in scale, the Lystek project would be viewed as a demonstration project for further evaluation. Only a fraction of the overall school's food waste could be managed at the project site, so it was important to identify food sources that had been pre-processed prior to delivery to Lystek. This was an important component to avoid the potential for an additional permitting requirement of a solid waste facility permit. As long as food waste had been pre-processed at the UCSB dining halls and/or cafeterias, by hand separation or sorting to the extent possible, no additional permitting would be required. The Santa Barbara Environmental Health Services, the LEA, would be able to visually validate the acceptance criteria.

Lastly, normal health and safety protocols were put in place to protect employees (and potentially public visitors) from hazards associated with dealing with decomposing organic matter and the resultant by-products of methane, carbon dioxide; hydrocarbon-based fuels; mechanical operating equipment, and chemicals, liquids and the like. A site-specific Health and Safety manual was prepared for the facility. Routine/monthly safety meetings on appropriate topics and new process training was given to staffs.

Upon acceptance of the Lystek application by the CEC in 2017 for a grant award, the team identified three main permit items:

- Complete an Initial Study following the CEQA guidelines.
- Secure a Site Use Permit with the GSD.
- Secure a Permit-To-Operate (PTO) from the SBCAPCD for the applicable equipment.

California Environmental Quality Act

GSD, in cooperation with Lystek, engaged the services of Dudek, an environmental consulting company operating predominately in California. Their Santa Barbara office was familiar with both the GSD facility and the local requirements for an environmental review document. Dudek assisted in the development of a detailed project description which would form the basis for a CEQA determination. GSD served as the lead agency for this project.

After the initial study was completed, the lead agency was able to determine if the project could have a significant impact on the environment. The lead agency was able to propose appropriate mitigation measures to reduce any impacts to less than significant "to the maximum extent feasible." GSD then prepared a draft Negative Declaration (ND) and published the document for public review for at least 21 days. After comments were received and reviewed, the lead agency determined there was no significant changes to the project scope. The GSD Board of Directors voted to adopt the document and file a Notice of Determination (NOD) on November 26, 2018, within the 30-day statute of limitations for legal challenge.

Local Permits

A key partner in this project was GSD, which was willing to allow the colocation of the project within their facility property. A Site Use Agreement was negotiated between GSD and Lystek and was formally executed in May 2018. The agreement allows Lystek to install and operate the necessary equipment to execute the terms of the CEC grant agreement. The GSD facility has the ideal physical layout for this project due to the infrastructure existing at the site. The Electrical Program Investment Charge (EPIC) project components were conveniently situated to the east of the GSD dewatering building and are not visible from public roadways. In addition, the height of the EPIC equipment was such that it did not exceed the highest building structures on the GSD site.

In addition, Lystek requested a Substantial Conformity Determination and Land Use Permit from the County of Santa Barbara Planning and Development.

Air Permits

The project is located in unincorporated Santa Barbara County, which falls under the jurisdiction of SBCAPCD. Early consultation was held with the SBCAPCD as early as 2017 during the grant application stages. The Lystek team sought to fully understand the permitting requirements and to design the system to comply with SBCAPCD emission requirements. The initial Authority to Construct (ATC) for the system was filed in May 2018. Several months of review and follow-up was used to complete the process, and the ATC was formally approved in May 2019. This allowed the equipment to be delivered and installed at the GSD site. Construction and commissioning took approximately three months and the system was functional at the end of August 2019. As allowed for in the ATC, a final PTO was issued in April 2020. A subsequent ATC/PTO application and permit was filed and received for a diesel-operated engine to support the power requirements of the system. This was a short-term requirement and the unit was removed from the site in September 2020.

APPENDIX C:
Standard Analytical Methods

The following standard methods were used in analyses conducted by accredited laboratories on the samples collected during the project.

SM2540G is used to measure the quantity of total and volatile solids contained in a liquid sample. The liquid sample is collected and weighed, then placed in an oven and dried at set temperatures for set amounts of time. After the procedure, the sample is weighed again, and the masses remaining in the sample are usually expressed as a percentage by weight.

SM5560C is used to measure the quantity of volatile acids in a liquid sample. The liquids are separated from any solids in the sample, then distilled to collect the acids. The amount of volatile acids is then determined by titrating the distillate with a base to a known pH.

SM2320B is used to measure the quantity of total alkalinity in a liquid sample. A volume of liquid is titrated with sulfuric acid to a set pH, which is used to calculated the alkalinity in solution.

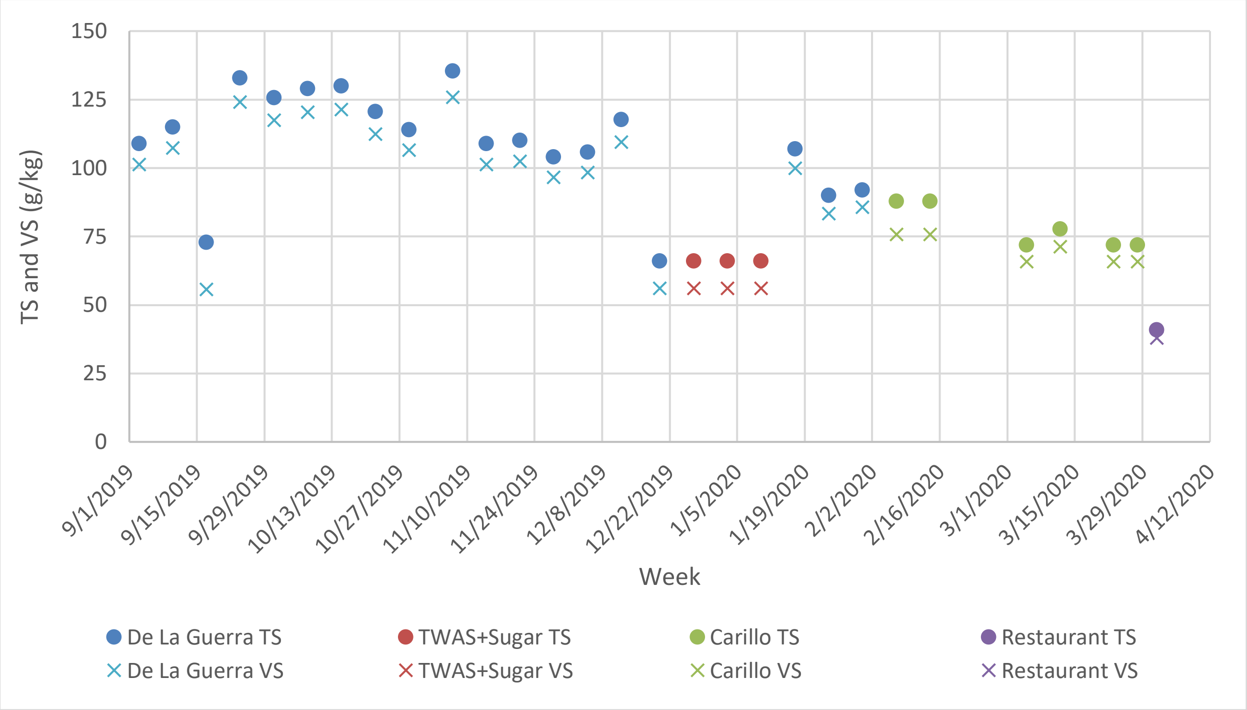
EPA 300.0 is a method that measures concentrations of inorganic ions (nitrite, nitrate, in this case) by using a specialized technique called ion chromatography. SM4500 is used to measure the total organic nitrogen and ammonia nitrogen in a sample. It is conducted by adding chemical reagents to a sample, which react with these molecules, coloring the liquid sample. The color is then analyzed by specialized equipment which determines the concentration of the ammonia and organic nitrogen. This is known as a colormetric method.

EPA350.1 works by the same principles as EPA300.0, but is used specifically to measure the concentration of ammonia in a liquid solution.

SM5220D measures the amount of chemical oxygen demand (COD), which is the amount of carbon that can be oxidized in a sample. It is also a colormetric method. The COD content is determined by adding a known volume of a specific reagent to the sample, and then analyzing the resulting color with a specialized machine.

APPENDIX D:
Supplmentary Operating Data

Figure D-1: Weekly Total Solids and Volatile Solids of Digester Feedstock

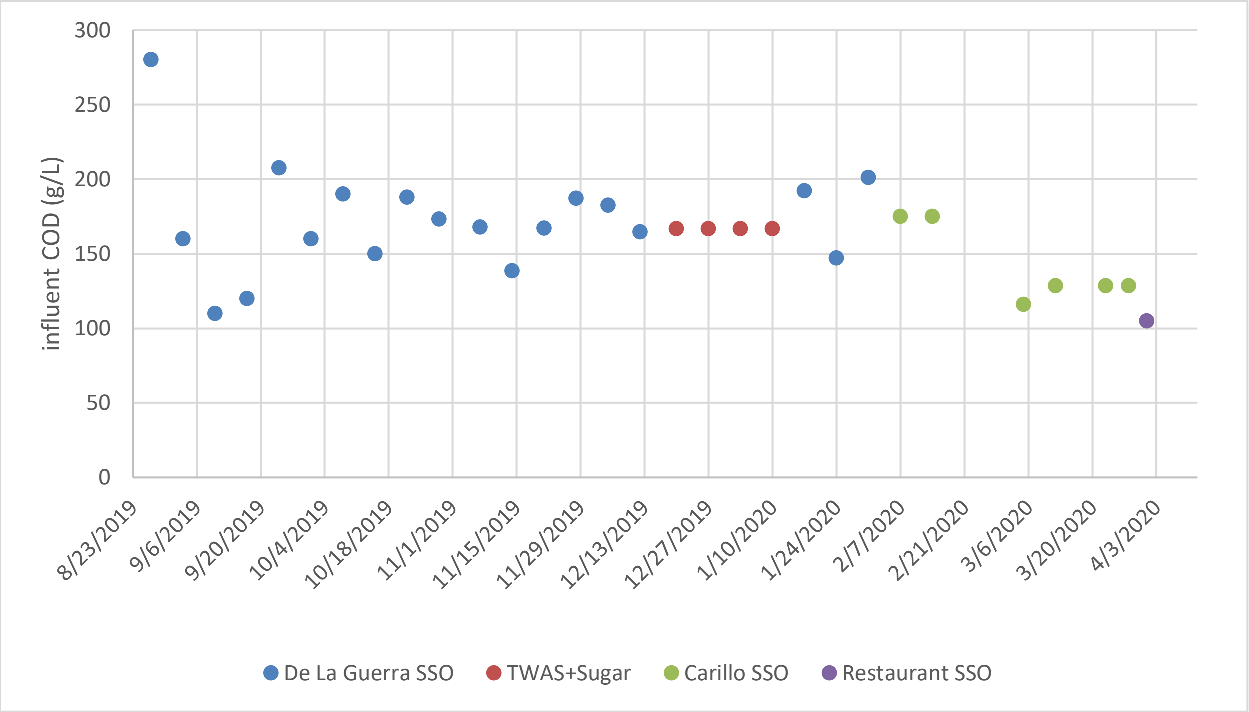


Source: Lystek International

Note that in the figure above, in weeks where the value is the same as the previous week, no analytical data were obtained.

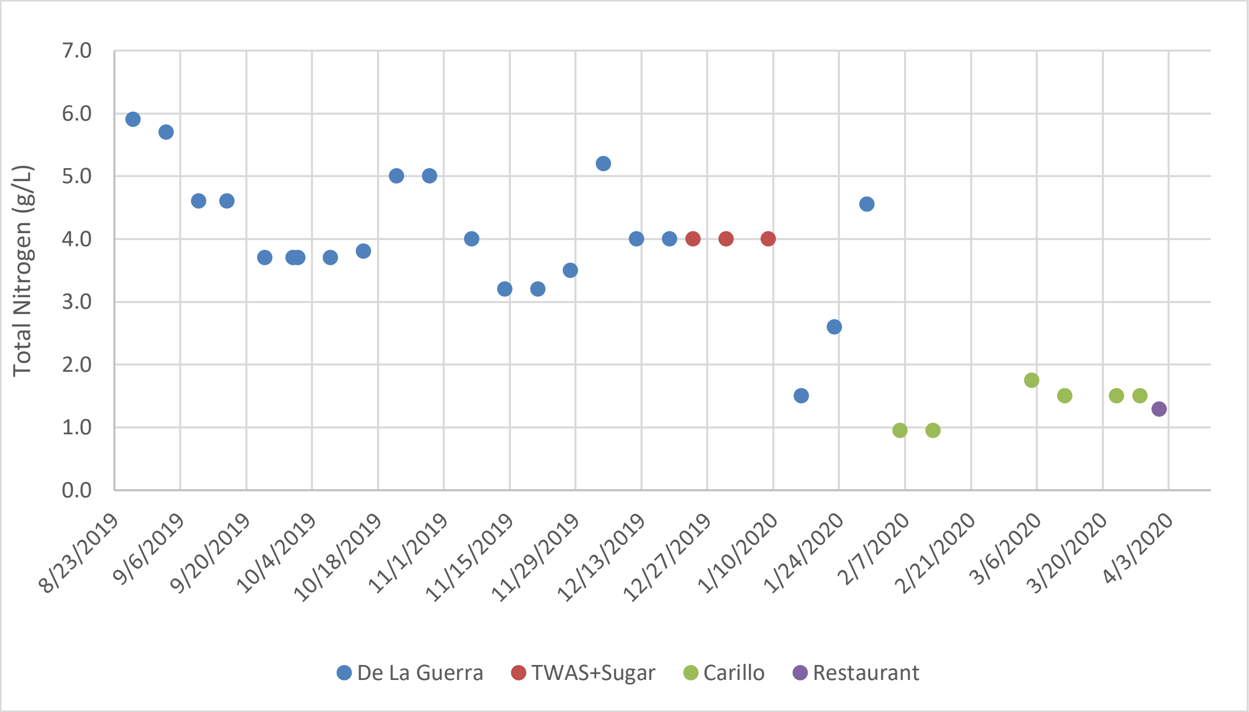
For all figures showing data on a weekly or bi-weekly basis, there is a three-week gap in the Carillo data, between February 13, 2020 to March 4, 2020 because the digesters were offline for cleaning. Operations resumed March 5, 2020.

Figure D-2: Influent Weekly Chemical Oxygen Demand



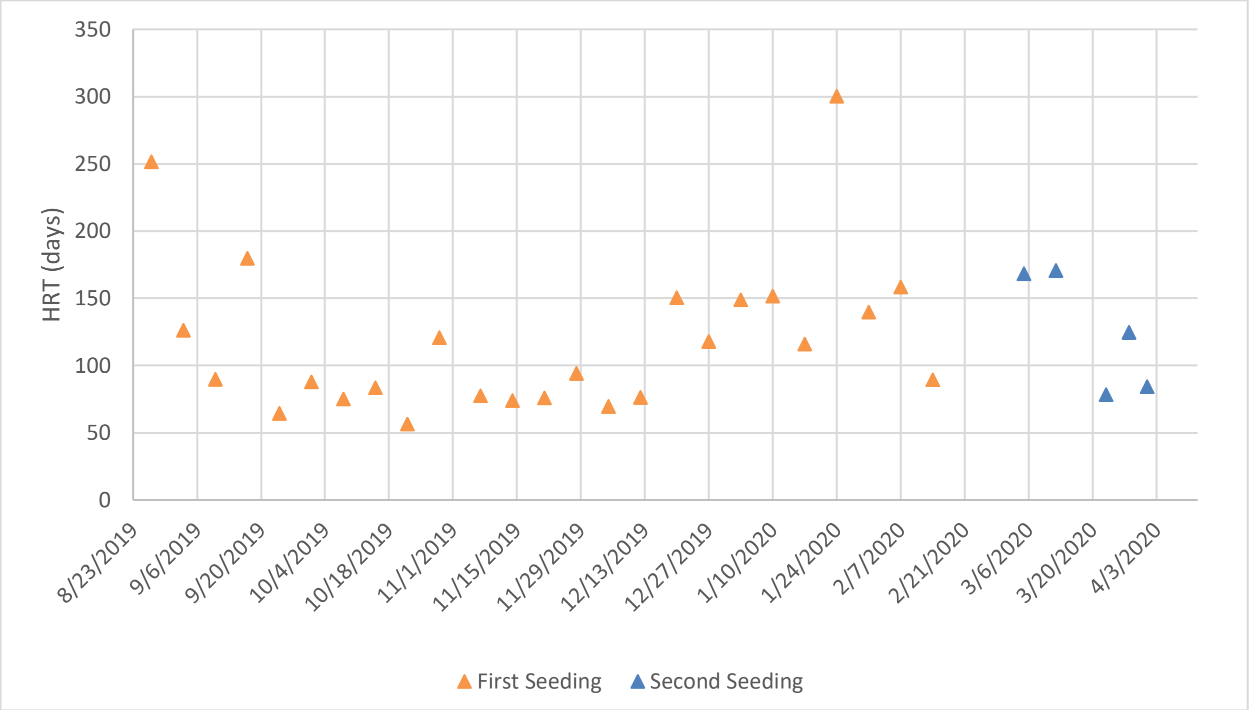
Source: Lystek International

Figure D-3: Total Nitrogen in Digester Feedstock on a Weekly Basis



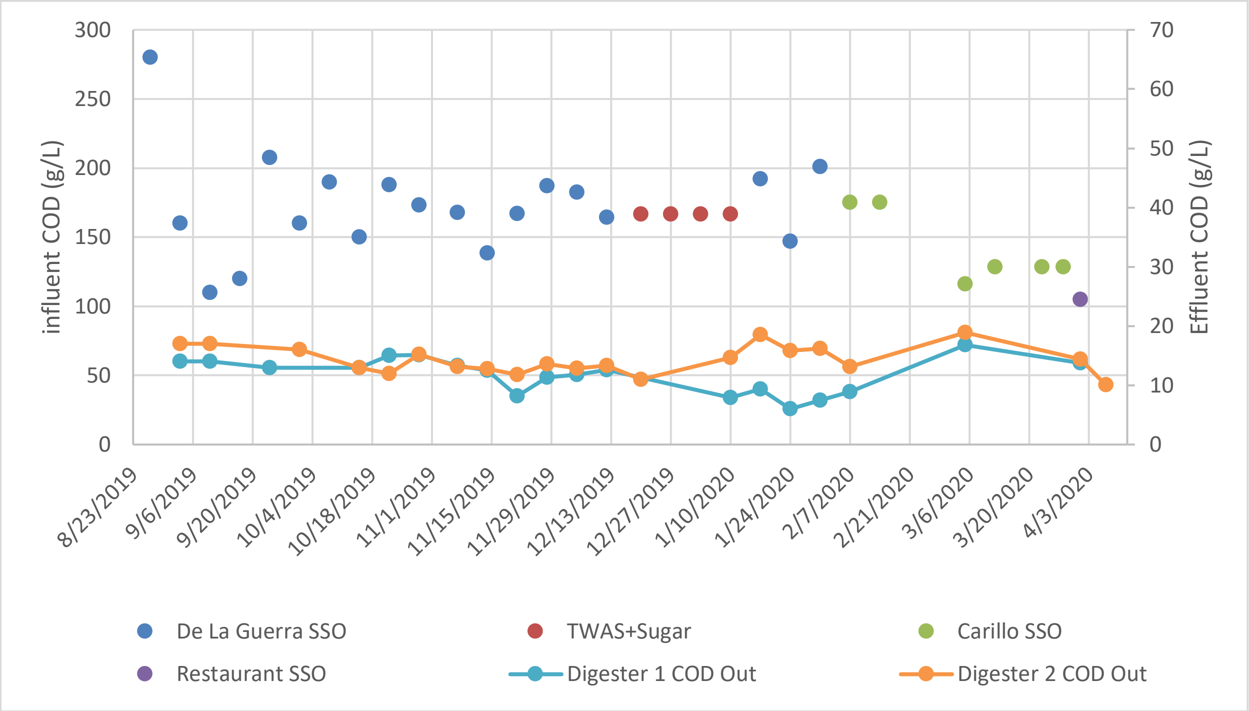
Source: Lystek International

Figure D-4: Digester Hydraulic Retention Time



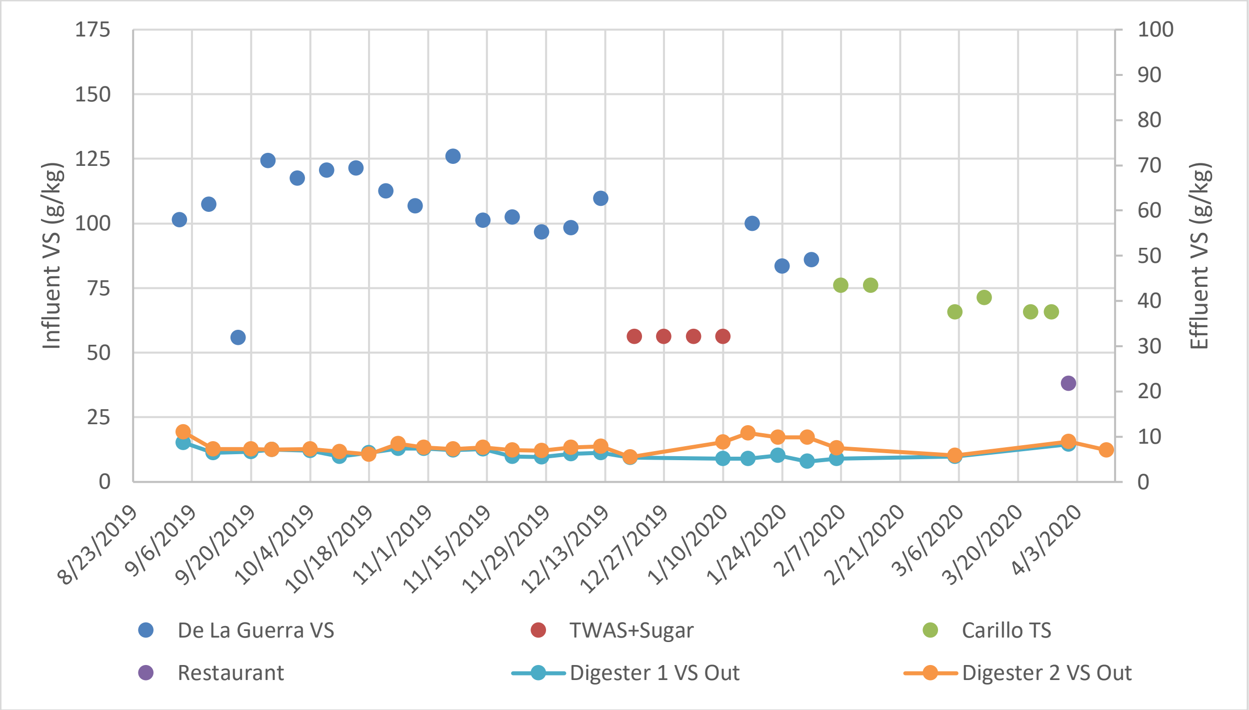
Source: Lystek International

Figure D-5: Influent and Effluent Chemical Oxygen Demand



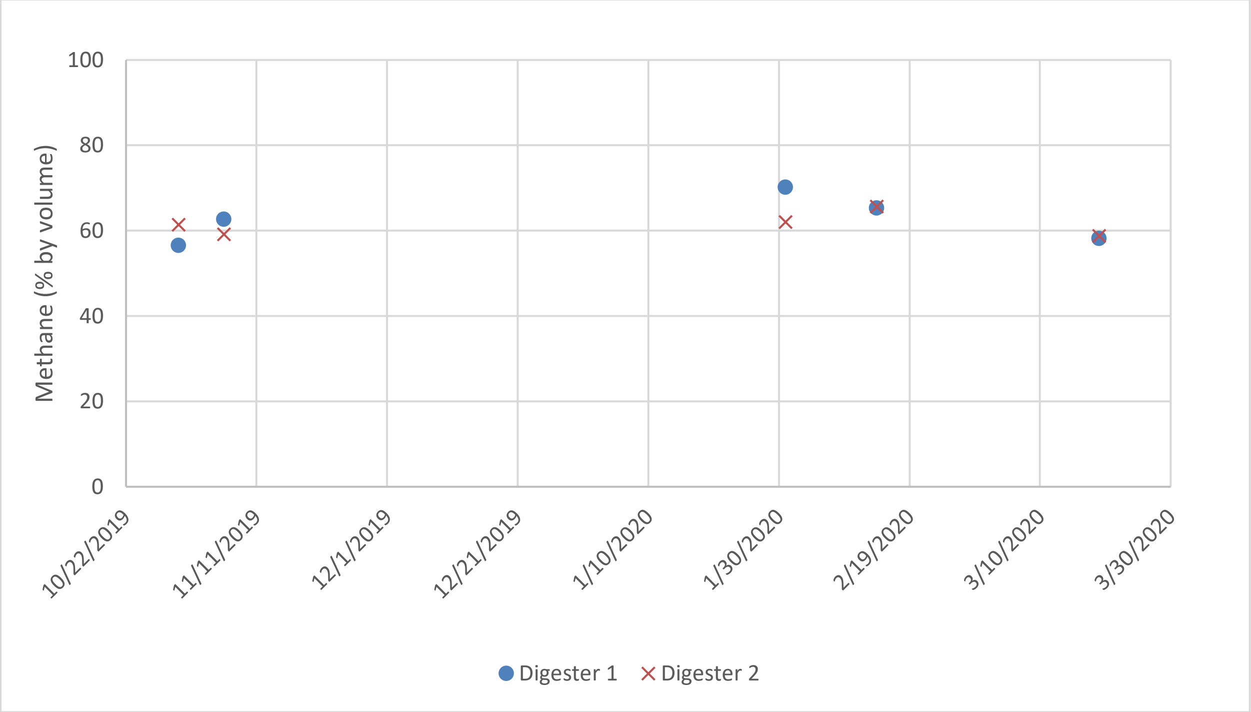
Source: Lystek International

Figure D-6: Influent and Effluent Volatile Solids



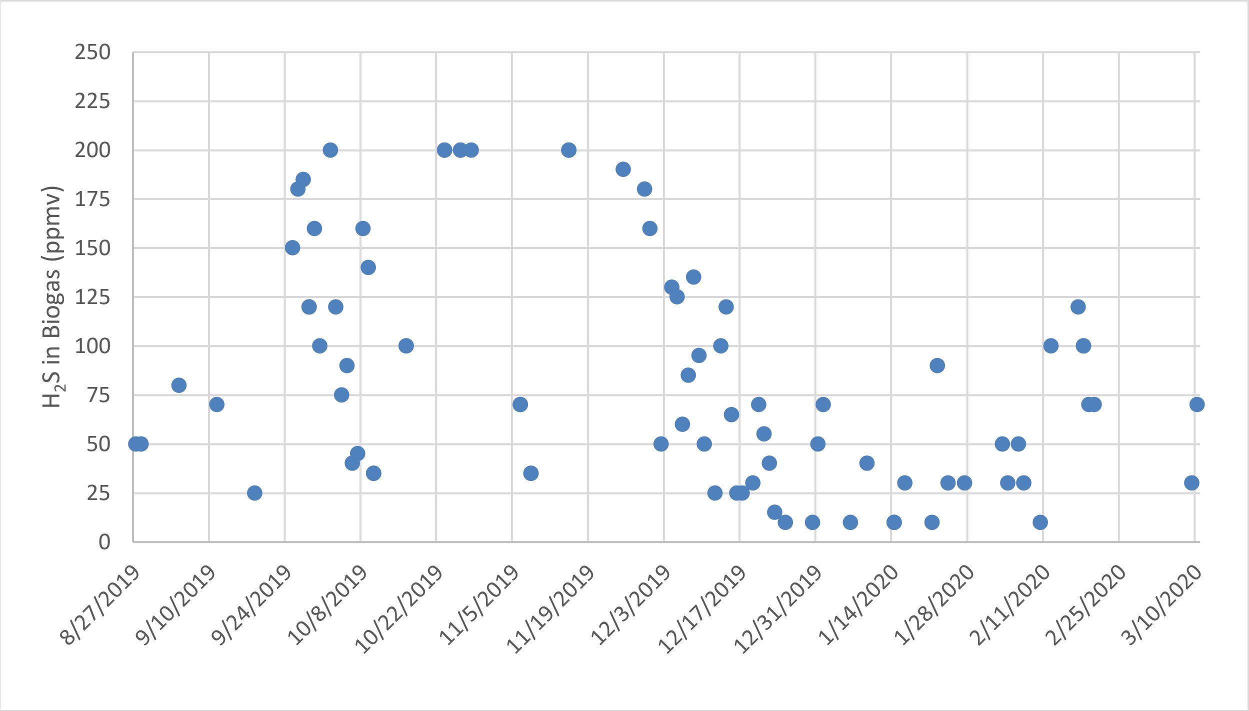
Source: Lystek International

Figure D-7: Digester Gas Methane Content



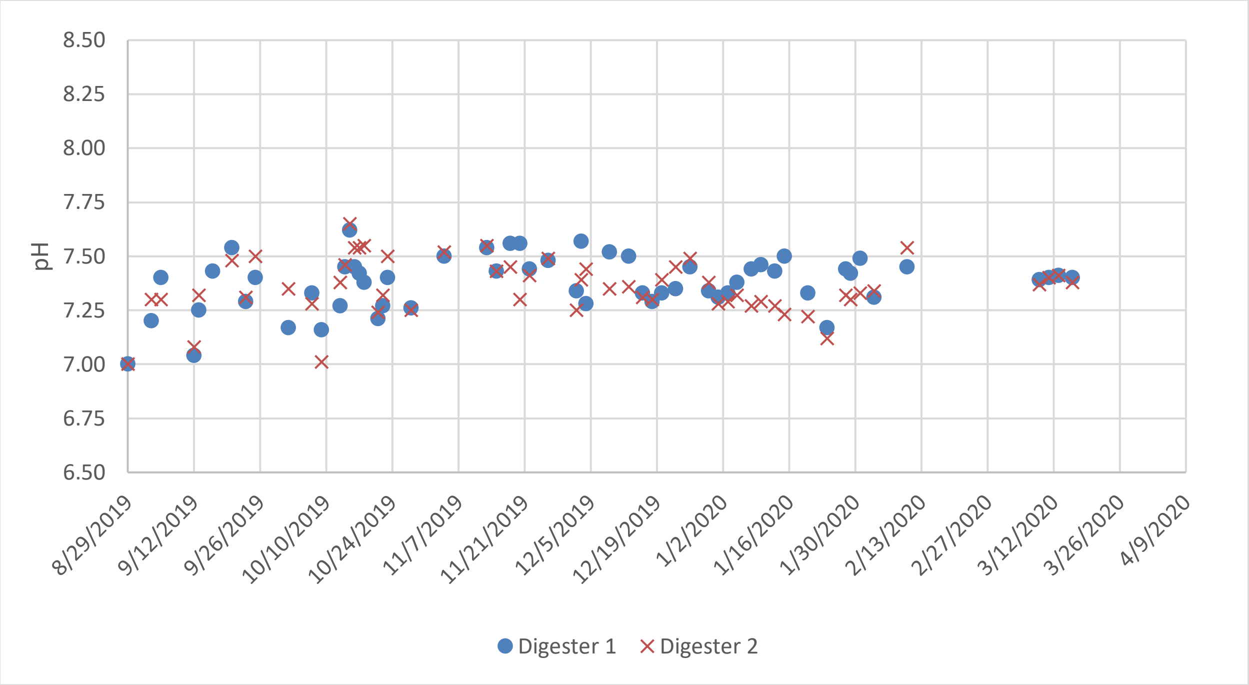
Source: Lystek International

Figure D-8: Hydrogen Sulfide Concentration in Biogas



Source: Lystek International

Figure D-9: pH in Digesters 1 and 2



Source: Lystek International

Table D-1 Ferric Chloride Addition Data

Date	Time	Operator	Amount Added (mL)
2019-08-27	0800 am	RH	800
2019-09-27	0700 am	RH	800
2019-10-02	0800 am	BT	800
2019-10-08	1030 am	BT	800
2019-10-14	0820 am	RH	100
2019-10-17	0940 am	BT	800
2019-10-24	0900 am	BT	800
2019-10-31	1030 am	BT	800
2019-11-06	0830 am	BT	1200
2019-11-11	0920 am	BT	1200
2019-11-14	0900 am	BT	1200
2019-11-18	1200 am	BT	1200
2019-11-21	0900am	BT	1200
2019-11-25	0930am	BT	1200
2019-11-27	1000 am	BT	1200
2019-12-07	0945 am	BT	1200
2019-12-08	0800 am	Alex West	1200
2019-12-09	0700 am	BT	1200
2019-12-10	1021 am	BT	1200
2019-12-11	1030 am	CM	1200
2019-12-12	0820 am	BT	1200
2019-12-13	0940 am	CM	1200
2019-12-14	0800 am	CM	1200
2019-12-15	0900 am	Alex West	1200
2019-12-16	0900 am	CM	1200
2019-12-17	0830 am	CM	1200
2019-12-18	0920 am	CM	1200
2019-12-19	1200am	CM	1200
2019-12-20	0900 am	CM	1200
2019-12-21	0900 am	Alex West	1200
2019-12-22	0900 am	Alex West	1200
2019-12-23	1040 am	BT	1200
2019-12-24	0830 am	CM	1200

Date	Time	Operator	Amount Added (mL)
2019-12-25	0800 am	BT	1200
2019-12-27	1000 am	CM	1200
2020-01-16	1100 am	CM	1200
2020-02-12	1040 am	CM	1200
2020-02-18	1030 am	CM	1200
2020-02-20	1015 am	CM	1200

Source: Lystek International

Table D-2: Co-digestion Case Economic Results

Component	Median Capital Cost	Average Annual O&M	Average Annual Revenue
Solid Organic Waste Receiving Station	($3,660,000)	($73,000)	
Dewatering	($2,650,000)	($53,000)	
Biogas Conditioning | Cogeneration	($3,340,000)	($67,000)	
Flare	($1,980,000)	($40,000)	
Biogas Beneficial Use | Cogeneration	($9,680,000)	($194,000)	
Overall Labor		($113,000)	
(Additional) Polymer		($300,000)	
Digestate Hauling and Tipping		($910,000)	
Food Waste Tipping			$1,800,000
Renewable Electricity Produced			$1,260,000
SGIP Credit	$77,000		
RINs			-
Total (Cost) or Revenue	($21,233,000)	($1,750,000)	$3,060,000
(Cost) or Revenue per Wet Short Ton of Food Waste at 30% Solids		($11)	

Source: Carollo, 2019

Table D-3: Food Waste Only Digestion Economic Results

Component	Median Capital Cost	Average Annual O&M	Average Annual Revenue
Solid Organic Waste Receiving Station	($3,660,000)	($73,000)	
Dewatering	($1,950,000)	($39,000)	

Component	Median Capital Cost	Average Annual O&M	Average Annual Revenue
Biogas Conditioning | Cogeneration	($3,430,000)	($69,000)	
Flare	($2,030,000)	($41,000)	
Biogas Beneficial Use | Cogeneration	($9,940,000)	($199,000)	
Overall Labour		($113,000)	
(Additional) Polymer		($220,000)	
Digestate Hauling and Tipping		($670,000)	
Food Waste Tipping			$1,800,000
Renewable Electricity Produced			$1,340,000
SGIP Credit	$77,000		
RINs (D5/D3)			$350,000 / $1,110,111
Total (Cost) or Revenue	($20,933,000)	($1,424,000)	$3,060,000 / $4,250,000
(Cost) or Revenue per Wet Short Ton of Food Waste at 30% Solids		$6 / $23	

Source: Lystek International

Table D-4: Levelized Cost of Energy Inputs

Technical Entries	Selected Case	User Modifications	Model Inputs
Project Capacity (MW)	2.86	-0.22	2.64
Capital Cost ($/kW)	7760	156	7916
Fixed O&M ($/kW)	392	146	538
Fixed O&M Escalation	2%	0%	2%
Variable O&M ($/MWh)	0	0	0
Variable O&M Escalation	0%	0%	0%
Fuel Cost ($/MBtu)	-7.50	-2.00	-9.50
Fuel Cost Escalation	2%	0%	2%
Heat Rate (Btu/kWh)	9000	-100	8900
Capacity Factor	90%	0%	90%
Financial Entries			
Debt Percentage	60%	10%	70%
Debt Rate	7%	-1%	6%
Debt Term (years)	15	5	20
Economic Life (years)	20	0	20
Depreciation Term (years)	7	8	15
Percent Depreciated	100%	0%	100%
Cost of Generation Escalation	0%	0%	0%
Tax Rate	40%	-14%	26%
Cost of Equity	10%	-2%	8%
Discount Rate	7%	0%	7%
Incentives			
PTC ($/MWh)	0	0	0
PTC Escalation	0%	0%	0%
PTC Term (years)	0	0	0
ITC	0%	0%	0%
Other Incentives ($/year)	0	0	0
Incentive Escalation (%)	0%	0%	0%

Source: Lystek International

Table D-5: Levelized Cost of Energy Fuel Cost Calculator

Fuel Cost Calculators (Manual)	Value
Solid Fuel	
$/dry ton	30
Heat content (BTU/pound)	9000
Fuel Cost ($/MBTU)	$1.67
Biogas Feedstocks	
$/wet ton tipping fee	20
Percent Solids	15%
Methane Yield (ft3/dry ton)	14,031
Fuel Cost ($/MBTU)	$9.50

Source: Lystek International

APPENDIX E:
Conference Abstracts

49th Annual SWANA Western Regional Symposium

6-month Project Update on Lystek's Food Waste Digestion at Goleta Sanitary District

Jim Dunbar, PE

ABSTRACT

This presentation will provide a 6-month update on Lystek's food waste digestion pilot project at Goleta Sanitary District (GSD) Water Resource Recovery Facility (WRRF). The project was awarded a US$1.6 million grant from the California Energy Commission (CEC) and will allow other WRRFs to test the modular skid-mounted system in the future.

Project Relevance:

Food waste digestion at WRRFs is one of the key solutions to increase diversion of organic waste from landfill disposal as mandated by California regulations (e.g., AB 1826, SB 1383). A 2017 assessment from the California Association of Sanitation Agencies (CASA) estimated that 'up to 75% of the food waste […] currently landfilled in the State could be received and processed by wastewater agencies through anaerobic digestion (AD)'.

Leveraging AD capacity at WRRFs enables projects to come online faster and at a lower cost than developing new standalone facilities since the infrastructure and onsite expertise already exist. In addition, processing food waste can offer additional revenues to WRRFs from increased biogas generation and tipping fees. However, WRRF operators are often reluctant to receive new feedstocks due to concerns over contaminants which may clog or damage piping and pumps, increased grit accumulation in digesters, potential toxic side-effects from heavy metals or ammonia buildup, potential for odors, permitting requirements, and increased quantity of biosolids. This pilot project addresses these concerns using mobile units for testing and education purposes.

Project Description:

The system can process both biosolids and source-separated organics (SSO). The SSO is pre-processed using Smicon depackaging equipment, a European technology producing a clean, high-organic slurry with less than 1% inorganic contamination by weight. While there are hundreds of Smicon machines worldwide since 2006, this 5-ton per hour (tph) test unit is the first in the US.

Two identical 2,100-gallon mesophilic anaerobic digesters and a 400-gallon Lystek-patented thermal hydrolysis process (THP) reactor are available to compare performance depending on the feed mix. The testing program include varying co-digestion ratio of biosolids and food waste, as well as different configuration and refeeding ratio of thermal hydrolysis product. Lystek THP combines high-speed shearing, alkali addition and low-pressure steam injection. It can be used pre-AD to pre-process organics and increase gas yield, or post-AD to stabilize digestate. The THP product is a nutrient-rich liquid and pumpable high solids (15-17%) Class A quality biofertilizer with unrestricted use.

Preliminary Results:
Weekly loads of source-separated pre- and post-consumer food waste from dining commons at the University of California Santa Barbara (UCSB) are being processed since August 2019. The total solids (TS) content of the SSO slurry feed ranges from 11% to 19%, total volatile solids average 93% of TS and total nitrogen is under 6,000 mg/L. The first month of operation showed healthy digesters with neutral pH (7.0 - 7.5), mesophilic temperature (98.5°F), and evidence of biogas production. Ammonia concentrations in the digesters are around 500 mg/L, well below any potential risk for inhibition. The VFA / alkalinity ratios also remain below the 0.4 threshold, which would indicate risk of digester acidification and failure.

LEARNING OBJECTIVES

- Understand the benefits and challenges of food waste digestion at Water Resource Recovery Facilities, which is one of the key solutions to increase diversion of organic waste from landfill disposal.
- Discover key results and lessons learned from 6+ months of operations from an innovative food waste processing pilot project, including depackaging, anaerobic digestion and thermal hydrolysis.
- Understand key aspects of developing a successful organic waste diversion project with public, private and international partners.

Waste Expo 2019

Initial Results from Codigestion and Thermal Hydrolysis Pilot Project using Food Waste and Biosolids

Jim Dunbar, PE (Lystek)

This presentation will discuss the initial results of Lystek's co-digestion pilot project at Goleta Sanitary District's Wastewater Treatment Plant (WWTP). The Project was awarded a US$1.5 million grant from the California Energy Commission (CEC) to deploy an environmentally and economically sustainable organics-to-energy system. Source-separated food waste from the University of California Santa Barbara will be preprocessed and co-digested with biosolids from the host WWTP in mobile skid-mounted demonstration units. The system will also include a centrifuge and thermal hydrolyser to convert the digestate into a valuable liquid biofertilizer, and a fuel-cell-based combined heat and power (CHP) unit operating on biogas. The goal of the Project is to demonstrate an integrated solution with depackaging efficiency (less than 1% contamination levels), successful integration with existing WWTP, improved biogas yield and increased energy generation from co-digestion and thermal hydrolysis.

BioCycle 2019

Food Waste Digestion Pilot Project at Goleta Sanitary District

Jim Dunbar, PE (Lystek)

This presentation will discuss the initial results of Lystek's co-digestion pilot project at Goleta Sanitary District (GSD)'s Water Resource Recovery Facility (WRRF). The Project was awarded a US$1.5 million grant from the California Energy Commission (CEC) to deploy an environmentally and economically sustainable organics-to-energy system.

Source-separated organics (SSO) from the University of California Santa Barbara (UCSB) is pre-processed and co-digested with biosolids from the host WRRF in mobile skid-mounted demonstration units. The SSO, which consist of pre- and post-consumer food waste from the campus dining commons, is depackaged by Smicon hammermill system. This European technology produces a clean, high-organic slurry at about 15-30% solids and less than 1% contamination by weight. Two identical 8-cubic meter mesophilic anaerobic digesters are available; one serves as control and the other is used for testing different codigestion ratio of biosolids and food waste, as well as different configuration and refeeding ratio of thermal hydrolysis product. Lystek patented thermal hydrolysis reactor (1.5 m^3) increases biogas yield (pre-digestion step or refeeding lysed material into digesters) and converts the digestate into a nutrient-rich liquid biofertilizer (post-digestion step).

The Project offers an integrated solution with high-efficiency depackaging, successful integration at existing WRRFs, improved biogas yield and increased energy generation from co-digestion and thermal hydrolysis. After the demonstration period at GSD, the mobile units will be available for testing at other WRRFs throughout North America.

Global Waste Management Symposium 2020

The Benefits of Digesting Food Waste at Water Resource Recovery Facilities: Results from the Goleta Sanitary District Pilot Project

Jim Dunbar, PE (Lystek) and Kim Domptail (GHD)

An increasing number of states and provinces throughout North America have implemented organics bans or set diversion targets from landfills in order to support greenhouse gas and waste reduction goals. For example, California AB 1826 (2014) requires businesses to recycle their organic waste depending on the amount of waste they generate per week. SB 1383 (2016) establishes targets to reduce statewide disposal of organic waste by 50% below 2014 levels by 2020 and 75% by 2025. These legislative initiatives require the separation, collection, and processing of organics (primarily food waste) from commercial, institutional, and residential sources.

Organic waste represent two-thirds of solid waste disposed at landfills in California, with food waste alone accounting for approximately 18% (5-6 million tons annually statewide). The California Association of Sanitation Agencies (CASA) 'estimates that up to 75% of the food waste, as well as fats, oil and grease (FOG), currently landfilled in the State could be received and processed by wastewater agencies through anaerobic digestion (AD)'.

Leveraging AD capacity at Water Resource Recovery Facilities (WRRF) enables projects to come online faster and at a lower cost than developing new standalone facilities since the infrastructure (digester, biogas handling, and wastewater treatment) and onsite expertise already exist. Organic waste diversion projects at WRRF require limited capital improvements, including food waste receiving facilities and AD upgrades to improve mixing and heating. These projects minimize the impact of transport because WRRFs are often located closer to dense urban areas where food waste is generated, while composting facilities and landfills are typically remote and farther away. In addition, processing food waste can offer additional revenues to the WRRF through increased biogas generation and thus energy production, and tipping fees.

However, WRRF operators are often reluctant to receive new feedstocks due to concerns over contaminants which may clog or damage piping and pumps, increased contaminant accumulation in digesters reducing overall residence time, potential toxic side-effects which may upset the digesters microbial activity, potential for odors, permitting requirements, and increased quantity of biosolids. The Lystek pilot project at Goleta Sanitary District (GSD) addresses several of these concerns using mobile skid-mounted units, including depackaging, anaerobic digestion, thermal hydrolysis and energy conversion technologies.

The main characteristics and objectives of the project include:

- Feedstock: The system can process digested biosolids from GSD and source-separated food waste from the University of California Santa Barbara (UCSB), including pre- and post-consumer food waste from the campus dining commons.
- Depackaging: The food waste is pre-processed using Smicon depackaging equipment, a European technology producing a clean, high-organic slurry at about 15-30% solids and

less than 1% contamination by weight. Table 1 briefly describes the major type of depackaging technologies and associated performance.

Table 1. Performance of depackaging equipment (% of contaminant-free organics) by technology type

Category	Description	Example	Performance
Extrusion	High-pressure systems extrude organics against mesh plates, water is added afterwards to dilute the resulting organic slurry, and grit particles are removed.	Anaergia OREX press	>90%[30]
Pulping	Mix food waste with process water, allowing for density-driven separation of light materials (plastics) and heavy materials (heavy inerts), followed by grit removal.	BTA® Waste Pulper	> 90%[31]
Milling	Horizontal or vertical paddle or hammer mills batter food waste and isolate organics through a mesh, followed by grit removal.	Smicon, Tiger	> 99%[32]

- Anaerobic digestion: Two identical 8-cubic meter mesophilic anaerobic digesters are available; one serves as control and the other is used for testing different codigestion ratio of biosolids and food waste, as well as different configuration and refeeding ratio of thermal hydrolysis product. Table 2 summarizes key typical characteristics of mesophilic anaerobic digestion of municipal wastewater sludge and food waste. Key elements of the testing program include:
    i. Stable digester operation and efficient organic conversion performance of at least 65% volatile solids reduction (VSR), without process upsets.
    ii. Biogas yield per ton of incoming feedstock 30% higher than the actual biogas production generated by the existing on-site digestion at GSD.
    iii. Biogas production of consistent quality (adequate and steady methane concentration of 60%) to produce electricity.

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[30] Anaergia OREX press: https://www.anaergia.com/what-we-do/municipal-solid-waste/organics-extraction

[31] BTA Waste Pulper: http://www.bta-international.de/en/der-bta-prozess/schluesselkomponente/bta-abfall-pulper.html

[32] Ecoverse Tiger: https://www.ecoverse.net/wp-content/uploads/2018/11/Ecoverse-Tiger-brochure.pdf

Table 2. Typical characteristics of mesophilic anaerobic digestion of food waste vs. sludge

Parameter	Sewage Sludge	Food Waste
Volatile Solids in Feed (% of total solids)	60-80%	85-90%
Volatile Solids Reduction (VSR)	25-65%	75-90%
Methane Yield[33] (L CH_4 per kg $VS_{destroyed}$)	625-660	650
Methane Yield (L CH_4 per kg $VS_{fed\ to\ digester}$)	250-360	560

- Thermal hydrolysis: Lystek patented thermal hydrolysis reactor (1.5 m^3) can process as a pre-digestion or post-digestion step.
    i. Pre-processing organics through thermal hydrolysis before AD can result in 10% additional gas yield.
    ii. Processing anaerobically digested biosolids through thermal hydrolysis and refeeding at least 30% of this material into digesters results in substantially higher volatile solids breakdown (up to 33%), higher gas yields (up to 50%) and reduced biosolids quantities.
    iii. Using thermal hydrolysis as a finishing step after anaerobic digestion stabilizes the organic fraction and creates a nutrient-rich liquid and pumpable high solids (15-17%) Class A quality biofertilizer product with unrestricted use.
- Energy conversion: The additional biogas generation translates into an extra four kilowatts of power generation capacity over the existing capacity on an equivalent volume basis.

The Project was awarded a US$1.5 million grant from the California Energy Commission (CEC)'s Electric Program Investment Charge (EPIC) Program and will provide other facilities with the ability to demonstrate the mobile unit(s) in the future.

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[33] Water Environment Federation: https://www.wef.org/globalassets/assets-wef/3---resources/online-education/webcasts/presentation-handouts/presentation-handouts---advanced-digestion-from-operators-perspective-11-2-17.pdf

Food Waste Co-Digestion at Water Resource Recovery Facilities: Results from the Goleta Sanitary District Pilot Project

Jim Dunbar, PE

ABSTRACT

Food waste co-digestion at Water Resource Recovery Facilities (WRRF) is one of the key solutions to increase diversion of organic waste from landfill disposal. This presentation will discuss the results and lessons learned from Lystek's food waste co-digestion pilot project, which was commissioned in August 2019 at the Goleta Sanitary District (GSD) in California. The project was awarded a US$1.5 million grant from the California Energy Commission (CEC)'s Electric Program Investment Charge (EPIC) program and will allow other WRRFs to test the modular skid-mounted system in the future.

General Background and Project Relevance:

An increasing number of states and provinces throughout North America have implemented organics bans or set diversion targets from landfills in order to support greenhouse gas and waste reduction goals. For example, California AB 1826 (2014) requires businesses that generate four cubic yards or more of commercial solid waste per week to recycle their organic waste. SB 1383 (2016) establishes targets to reduce statewide disposal of organic waste by 50% below 2014 levels by 2020 and 75% by 2025. These legislative initiatives require the separation, collection, and processing of organics (primarily food waste) from commercial, institutional, and residential sources. Food waste alone accounts for approximately 18% of solid waste disposed at landfills in California (5-6 million tons annually statewide). A 2017 assessment from the California Association of Sanitation Agencies (CASA) estimated that 'up to 75% of the food waste, as well as fats, oil and grease (FOG), currently landfilled in the State could be received and processed by wastewater agencies through anaerobic digestion (AD)'.

Leveraging AD capacity at WRRFs enables projects to come online faster and at a lower cost than developing new standalone facilities since the infrastructure (anaerobic digesters, biogas handling equipment, and wastewater treatment system) and onsite expertise already exist. Organic waste diversion projects at WRRFs require limited capital improvements, including food waste receiving facilities and AD upgrades to improve mixing and heating. These projects minimize the impact of transport because WRRFs are often located closer to dense urban areas where food waste is generated, while composting facilities and landfills are typically remote and farther away. In addition, processing food waste can offer additional revenues to WRRFs through increased biogas generation and thus energy production, as well as tipping fees per ton of food waste or organic slurry received.

However, WRRF operators are often reluctant to receive new feedstocks due to concerns over contaminants which may clog or damage piping and pumps, increased grit accumulation in digesters reducing overall residence time, potential toxic side-effects from heavy metals or ammonia buildup which may upset the digesters microbial activity, potential for odors, permitting requirements, and increased quantity of biosolids. This pilot project addresses several of these concerns using mobile skid-mounted modular units for testing and education purposes.

Project Description:
The system can process both biosolids and source-separated organics (SSO). The SSO is pre-processed using Smicon depackaging equipment, a European technology producing a clean, high-organic slurry between 10 and 30% solids and less than 1% inorganic contamination by weight. While there are hundreds of Smicon machines worldwide since 2006, this 5-ton per hour (tph) test unit is the first in the US.

Two identical 2,100-gallon mesophilic anaerobic digesters and a 400-gallon Lystek-patented thermal hydrolysis process (THP) reactor are available to compare digester performance depending on the feed mix. The testing program include varying co-digestion ratio of biosolids and food waste, as well as different configuration and refeeding ratio of thermal hydrolysis product. Lystek THP combines high-speed shearing, alkali addition and low-pressure steam injection. It can be used pre-AD to pre-process organics and increase gas yield, or post-AD to stabilize digestate. Refeeding hydrolysed material into the digesters results in substantially higher volatile solids breakdown, higher gas yields and reduced biosolids quantities. The THP product is a nutrient-rich liquid and pumpable high solids (15-17%) Class A quality biofertilizer with unrestricted use.

Results and Lessons Learned:
Weekly loads of source-separated pre- and post-consumer food waste from dining commons at the University of California Santa Barbara (UCSB) are being processed since August 2019. The total solids (TS) content of the SSO slurry feed ranges from 11% to 19%, total volatile solids average 93% of TS and total nitrogen is under 6,000 mg/L. Table 1 summarizes the characteristics of the SSO feed. The digesters were seeded with GSD sludge and immediately fed SSO slurry. The first month of operation showed healthy digesters with neutral pH (7.0 - 7.5), mesophilic temperature (98.5°F), and evidence of biogas production. Ammonia concentrations in the digesters are around 500 mg/L, well below any potential risk for inhibition. The VFA / alkalinity ratios also remain below the 0.4 threshold, which would indicate risk of digester acidification and failure.