California Energy Commission

Clean Transportation Program

FINAL PROJECT REPORT

Enhanced Transportation Biomethane Production From Municipal Sludge Digesters

Prepared for: California Energy Commission

Prepared by: Sacramento Municipal Utility District

Gavin Newsom, Governor

January 2020 | CEC-600-2020-011

California Energy Commission

Valentino Tiangco – Sacramento Municipal Utility District
Meltem Urgun-Demirtas - Argonne National Laboratory
Josh Rapport - CleanWorld
Matt Hart - TSS Consultants
Primary Authors

Sacramento Municipal Utility District
6301 S Street
Sacramento, CA 95814
SMUD Website www.smud.org

Agreement Number: ARV-10-003

Patrick Brecht
Project Manager

John P. Butler II
Acting Office Manager
ADVANCED VEHICLE INFRASTRUCTURE OFFICE

Kevin Barker
Deputy Director
FUELS AND TRANSPORTATION

Drew Bohan
Executive Director

ACKNOWLEDGEMENTS

The California Energy Commission sponsored this work. The submitted manuscript for the final project report is a team effort by SMUD, Argonne National Laboratory, CleanWorld and TSS Consultants. The authors also would like to thank Stickney Water Reclamation Plant of Metropolitan Water Reclamation of District of Greater Chicago and Woodridge Greene Valley Wastewater Facility located at Woodridge, IL for providing sludge samples from their plants.

PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program, formerly known as the Alternative and Renewable Fuel and Vehicle Technology Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued solicitation PON-09-003 to provide funding opportunities under the Clean Transportation Program for projects that involve the design, construction, and operation of biomethane facilities. In response to PON-09-003, the recipient submitted an application which was proposed for funding in the CEC's notice of proposed awards on April 7, 2010. The agreement was executed as ARV-10-003-01 by SMUD Energy Research and Development Department on June 24, 2011 in the amount of $1.8 million.

ABSTRACT

The goal of this Agreement is to develop, demonstrate, and deploy an innovative approach to enhancing biogas production. The project team seeks to produce a biomethane transportation fuel that reduces greenhouse gas emissions, petroleum demand, and the environmental impacts associated with co-digestion of waste water, sludge, food waste and other organic wastes. The main objective of this project is to enhance anaerobic digestion of organic biosolids at wastewater treatment plants using a modified version of Argonne National Laboratory's patented process (US 8,247,009 and US Patent Application No.14/540,393). This new process has the potential to increase the productivity of anaerobic digestion process by a factor of five and reduce the amount of carbon dioxide. Biogas from anaerobic digestion of organic materials consists of methane, carbon dioxide and other trace components, which can be upgraded for use in combined heat and power systems or as vehicle fuel.

Argonne achieved this breakthrough process by using a waste material (biochar) with high concentrations of mono- and divalent cations such as potassium, calcium and magnesium which can stimulate accelerated carbonation for carbon dioxide sequestration. Biochar is a waste product from thermochemical conversion of biomass via gasification and pyrolysis. Anaerobic digestion of food waste was conducted in batch and two-stage semi-continuous configurations at two different scales bench- (0.5 L), pilot- (14 L) and field-scale (100,000 gallons). The bench- and pilot-scale tests were conducted at Argonne National Laboratory while the field-scale tests were conducted at the American River Packaging Plant in Sacramento.

Results from bench and pilot scale tests at Argonne National Laboratory showed methane content increasing up to 1.1 times and carbon dioxide decreasing up to 3.3 times. Field scale tests in Sacramento showed methane content increasing up to 1.2 times and carbon dioxide decreasing up to 1.8 times. These positive results led to increased production of transportation fuel and electricity. Overall, this new process could provide an economic waste-to-energy process, reduce greenhouse gas emissions, reduce demand for fossil fuels, and reduce environmental impacts associated with major California's waste sources.

Keywords: California Energy Commission, wastewater treatment plants, sewage sludge, food waste, CO_2 sequestration, biomethane, biogas

Please use the following citation for this report:

Valentino Tiangco, Meltem Urgun-Demirtas, Jessica Linville, Yanwen Shen, Seth Snyder, Josh Rapport, Matt Hart, Frederick Tornatore. 2020. *Enhanced Transportation Biomethane Production from Municipal Sludge Digesters.* California Energy Commission. Publication Number: CEC-600-2020-011.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Page

EXECUTIVE SUMMARY

Introduction

The Sacramento Municipal Utility District (SMUD) is working to enhance the growth of local biogas systems by optimizing biogas production and improving the efficiency of anaerobic digesters. Eurisko, the initial Prime Contractor, provided private matching funds for this project, with SMUD as a key partner. Eurisko abandoned the California Energy Commission (CEC) grant in 2012 and the CEC agreed to novate the agreement from Eurisko to SMUD as the Prime Contractor, with Argonne National Laboratory (Argonne) and CleanWorld as key partners at the February 13, 2013 Business Meeting.

Background

California uses more than two trillion cubic feet of natural gas per year.[1] Natural gas provides more than half of the state's electricity, heating and cooling, and a growing share of transportation fuels. Although cleaner and cheaper than petroleum fuels, natural gas is a major source of greenhouse gas (GHG) emissions, air and water pollution. California imports 91 percent of its gas, making the state vulnerable to supply and price fluctuations and costing more than $9 billion per year in lost revenues and jobs.[2] Natural gas contains more than 95 percent methane (CH_4), which burns cleanly and efficiently, and emits much less carbon dioxide (CO_2) than coal or petroleum. While cleaner than coal, natural gas is still a fossil fuel. However, biomethane can replace natural gas for the production of heat and power and/or co-generation, vehicle fueling, chemicals production and injection into the natural gas grid.[3] Increasing the use of biomethane will reduce GHG emissions positively, significantly reduce petroleum fuel demand, stimulate economic development, and reduce environmental impacts associated with California's major waste sources.

Recently, the U.S. Environmental Protection Agency (U.S. EPA) ruled that biomethane from landfills and anaerobic digesters qualifies as a cellulosic biofuel as specified under the Renewable Fuel Standards if it is used for transportation. With this new ruling, biogas can generate Renewable Identification Number credits for the producer.[4]

---

1 California Energy Commission. 2014. *Overview of Natural Gas in California*. CEC Energy Almanac. [CEC webpage about natural gas](https://ww2.energy.ca.gov/almanac/naturalgas_data/overview.html): https://ww2.energy.ca.gov/almanac/naturalgas_data/overview.html

2 Julia Levin, Mitchell, K., Swisher. 2014. *Decarbonizing the Gas Sector: Why California Needs a Renewable Gas Standard.* Bioenergy Association of California.

3 L Lombardi, Carnevale, E. 2013. *Economic Evaluations of an Innovative Biogas Upgrading Method with CO2 Storage. Energy*, 62, 88-94.

4 U.S. Environmental Protection Agency. 2014. RFS Renewable Identification Number (RIN) Quality Assurance Program; Final Rule. *40 CFR Part 80*, Vol. 79, United States Environmental Protection Agency. Washington, DC.

Wastewater Treatment Plants and Biogas Production

In the U.S., wastewater treatment plants treat approximately 32.3 billion gallons of wastewater each day at about 14,780 facilities, resulting in approximately 6.5 million metric tons (dry weight) of sewage sludge annually.[5] One of the most efficient and widely used technologies for the treatment of sludge from wastewater treatment plants is anaerobic digestion, a naturally occurring biological process involving the degradation and stabilization of organic materials under anaerobic conditions.[6] In the U.S., 14 percent of all municipal solid waste - 35 million tons per year - is classified as organic food waste.[7] Food waste is rich in energy content and its addition to an anaerobic digestion system could significantly improve the biogas yields.[8] However, food waste can pose challenges to the anaerobic digestion process due to high solids content and chemical composition.[9] Two-stage anaerobic digestion systems are less susceptible to process upsets due to the optimization of each digester for the distinctly different microbes that carry out the acid fermentation and methanogensis stages.[10]

Biogas produced from anaerobic digestion of sludge is composed of 50-70 percent methane (CH_4) and 30-50 percent CO_2, with smaller amounts of hydrogen sulfide (H_2S), ammonia (NH_3) and nitrogen (N_2).[3] Biogas produced from anaerobic digestion of organic materials can be cleaned and upgraded to biomethane for heat and power generation through costly biogas upgrading processes. The biogas upgrading process includes removal of CO_2 and trace contaminants. Most gas companies require the biogas to have a level of purity similar to that of natural gas, with greater than 96 percent methane content and a minimum heating value of 37 megajoule/m^3 before utilization.[11] These biogas upgrade technologies increase the costs of biomethane production by 20-72 percent because of high operating pressure, electricity,

5 U.S. EPA. 2010. *Clean Watersheds Needs Survey 2008 - Report to Congress*. U.S. Environmental Protection Agency. Report No. EPA-832-R-10-002.

6 Chen, Y., Cheng, J.J., Creamer, K.S. 2008. *Inhibition of anaerobic digestion process: A review*. *Bioresource Technology*, **99** (10), 4044-4064.

7 U.S. EPA. 2011. *Opportunities for combined heat and power at wastewater treatment facilities: Market analysis and lessons from the field.* United States Environmental Protection Agency.

8 Zhang, C.S., Su, H.J., Tan, T.W. 2013. Batch and Semi-Continuous Anaerobic Digestion of Food Waste in a Dual Solid-Liquid System. *Bioresource Technology*, **145**, 10-16.

9 Zhang, L., Jahng, D. 2012. Long-Term Anaerobic Digestion of Food Waste Stabilized By Trace Elements. *Waste Management*, **32** (8), 1509-1515.

10 Grimberg, S.J., Hilderbrandt, D., Kinnunen, M., Rogers, S. 2015. Anaerobic digestion of food waste through the operation of a mesophilic two-phase pilot scale digester - Assessment of variable loadings on system performance. *Bioresource Technology*, **178**, 226-229.

11 Shen, Y., Linville, J.L., Urgun-Demirtas, M., Mintz, M.M., Snyder, S.W. 2015a. An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: challenges and opportunities towards energy-neutral WWTPs. *Renewable & Sustainable Energy Reviews*, **50**, 346–362.

chemical and water requirements and loss of methane.[12] However, with a more cost competitive technology, the high costs associated with the use of anaerobic digestion could be eliminated or minimized. Currently, only 48 percent of the total wastewater flow in the U.S. is treated with anaerobic digestion [13] and less than 10 percent of the waste water treatment plants using anaerobic digestion technology use the biogas as a low carbon substitute for heat and power generation. Further research is needed to make biomethane a more viable energy resource.

Increased Biogas Production from Biochar

The purpose of this project is to enhance the anaerobic digestion of biosolids at wastewater treatment plants using a modified version of Argonne's patented process. The Argonne treatment process captures and sequesters the CO_2 naturally produced during biomethane production. Argonne achieved this breakthrough by utilizing waste material (biochar) with high concentrations of mono- and divalent cations. Biochar is a waste product from thermochemical processing, such as gasification and pyrolysis, of lignocellulosic biomass under oxygen-starved conditions.[14] The biomass feedstock and processing conditions have significant roles in the composition of the biochar.[15] The biochar also provides supplemental nutrients including calcium, magnesium and iron for anaerobic digestion of sludge or food waste. These monovalent and divalent cations can stimulate accelerated carbonation for CO_2 sequestration. This process could enhance the economics of anaerobic digestion to make pipeline-quality biomethane that can be used in energy and power production, and compressed natural gas vehicles. Overall, the process could provide an economic waste-to-energy process, reduce GHG emissions, reduce demand for fossil fuels, and reduce environmental impacts associated with major US waste sources.

Sustainable feedstock supply is key to a successful demonstration of biodigesters. In the Sacramento area, commercial and residential food waste offers the greatest potential source of feedstock. This project assessed the biogas resources from food waste, fats, oils, greases, green waste, and animal manure.

---

12 Beil, M., Beyrich, W., Holzhammer, U., Krause, T. 2013. Biomethane, Agency for Renewable Resources. Gulzow-Pruzen, Germany.

13 Water Environment Federation. 2013. Biogas Production and Use at Water Resource Recovery Facilities in the United States. Water Environment Federation.

14 Brown, R.C. 2011. Thermochemical processing of biomass: Conversion into fuels, chemicals and power. in: *Wiley Series in Renewable Resource*, (Ed.) C. Stevens, Wiley. Great Britain.

15 Brewer, C.E., Schmidt-Rohr, K., Satrio, J.A., Brown, R.C. 2009. Characterization of Biochar from Fast Pyrolysis and Gasification Systems. *Environmental Progress & Sustainable Energy*, **28**(3), 386-396.

Field Trials and Results

SMUD and its partners conducted full-scale field trials at the CleanWorld digester using the biochar additive process developed during the bench and pilot-scale testing portion of the project at Argonne. The project team developed recommendations to modify multiple aspects of the anaerobic digestion process for the full-scale field trials in Sacramento; the costs of these recommendations were evaluated as part of the final economical assessment. Finally, the team made recommendations for additional research and development needed to make this technology commercially viable.

The project successfully demonstrated the ability to anaerobically digest food waste both with and without the biochar additive in the field. It also demonstrated that the biochar additive enhanced biogas quality (i.e. increased the methane concentration in the biogas produced) similar to the bench and pilot tests. Biogas production rates indicated highly efficient conversion of food waste to biogas, and after the addition of biochar, the methane content of the biogas increased.

For the field trial, a total of 96,100 gallons of feedstock were loaded into the digester during the pilot test, resulting in the production of 446,650 standard cubic feet (scf) of methane. In addition, 15,500 pounds of biochar were loaded over 12 weeks after running the digester for 6 weeks without biochar. The steady-state methane content increased from 66 percent before adding biochar to 78 percent after the biochar was added.

The higher methane content generally leads to higher methane recovery rates and higher quality tail gas off the CleanWorld biogas cleaning system. Methane content increased by a factor of 1.15 and CO_2 decreased by a factor 3.3 during the Argonne bench and pilot scale tests. During the field trials in California, methane content increased by a factor of 1.22 and CO_2 decreased by a factor of 1.8. These positive results led to increased production of biogas for use as a transportation fuel or electricity production.

At CleanWorld's Sacramento BioDigester facility, which has a 190kW generator, using the tail gas for electricity production would keep the generator running at full capacity over 95 percent of the year, which would boost annual revenues by $210,408. Increasing methane recovery for transportation fuel could add $140,000 to $200,000 to the system's annual revenues. After accounting for the capital, operating and maintenance costs of the biochar storage and loading equipment, this left from $290,000 to $350,000 in additional revenue with which to purchase biochar.

At the biochar loading rate used for this project, biochar would have to cost from $66 to $80 per ton for the project to be cost neutral. This is higher than the lowest current and projected market prices for biochar. However, reducing the loading rate by recycling biochar, or increasing revenues by selling biochar-enhanced digestate at a premium, could make this technology more cost effective. A market decrease in biochar prices could also make the technology economically viable. Future research should focus on biochar recycling and determining the value of digestate from a digester using biochar as an additive.

CHAPTER 1: Resource Assessment/Verification and Procurement Plan

The first task of the project was to perform a site-specific feedstock resource assessment (gross, technical and economic potentials) and feedstock procurement plan to determine the sustainable feedstock supply requirements for co-digestion possibilities in Sacramento.

Resource Assessment/Verification and Procurement Plan

The project team used a competitive solicitation process to select a contractor for the resource assessment. TSS Consultants of Rancho Cordova, California was selected to complete this task, which included the resource assessment, resource verification, procurement, and pilot collection activities. This chapter includes a synopsis and analyses of the following topics:

- Assessment of Biogas Resources
- Regional Infrastructure Analysis
- Pilot Program Planning
- Pilot Project Implementation
- Communication and Outreach

Assessment of Biogas Resources

Four types of organic waste were assessed:

- Food Waste
- Fats, Oils, and Greases (FOG)
- Green Waste
- Animal Manure

TSS assessed the gross, technical, and economic feedstock availability for four haul zones; 30-minute, 60-minute, 90-minute, and 120-minute drive times from the approximate center of SMUD territory. TSS analyzed costs to transport the organic feedstocks to the Sacramento-area anaerobic digesters (ADs) at the CleanWorld site – the American River Packaging (ARP) Facility and/or South Area Transfer Station (SATS) Facility. Each feedstock category was assessed for the residential and commercial waste generations. TSS conducted this study using existing literature and agency resources where possible, and supplemented the data with interviews of local waste haulers, waste generators, waste managers, and grass roots organizations.

Existing Infrastructure

Infrastructure for organic waste collection varies greatly by waste stream. Currently, green waste is collected for both residential and commercial customers. Tipping fees, or the price charged by transfer stations or landfills to accept waste, are structured to incentivize green waste separation. FOG is collected in two forms, yellow grease (e.g., frying grease), which is sold as commodity, and trap grease, which is generated at commercial businesses doing food preparation. Trap grease is hauled away by pump trucks and can be refined into a commodity, although it is more often disposed of at wastewater treatment facilities. Large volumes of animal manure (e.g., dairy farms) are managed onsite and regulated by the Central Valley Regional Water Quality Control Board to manage nutrient discharge.

Food waste diversion began to develop as a cost-saving mechanism for large food waste generators to reduce their waste disposal costs. Recently, the larger waste haulers have begun to adopt food waste collection routes for larger customers with voluntary opt-in participation. In the Sacramento area, the largest three waste haulers all have voluntary food waste recycling programs, which help supply the CleanWorld ADs with necessary organic feedstocks. Without legislative support or mandate, these programs have been limited to organizations participating out of a push for social responsibility, for "green" or "sustainability" marketing, or in some cases, reduced waste disposal costs. The growth of these programs have resulted in many lessons learned and will be invaluable to the focus and direction of the SMUD pilot and demonstration programs.

Organic Waste Availability

TSS estimated the volume of economically available organic waste feedstocks that could be used at CleanWorld's three Sacramento-area ADs. Currently, green waste and FOG are not economically available to these digesters due to processing and transportation costs, and alternative lower-cost disposal methods such as composting, alternative daily cover, and sale to existing biomass power plants. There are also lower cost disposal options at area wastewater treatment plants (WWTPs). Limited feedstock from animal manure is available from local sources such as stables, zoos, and farming operations where land application is not available. While dairy manure has gross and technical potential, the cost of transportation of this feedstock is prohibitively expensive.

In the Sacramento area, commercial and residential food waste offer the greatest potential source of feedstock. Table 1 summarizes the total organic waste availability, less ongoing feedstock demand from the existing CleanWorld digesters. The majority of the feedstock comes from commercial food wastes, followed by residential food waste (Figure 1).

Table 1: Overall Organic Waste Availability

HAUL DISTANCE	GROSS AVAILA-BILITY (TONS PER YEAR)	GROSS AVAILA-BILITY (TONS PER YEAR)	TECHNICAL AVAILABLITY (TONS PER YEAR)	TECHNICAL AVAILABLITY (TONS PER YEAR)	ECONOMIC AVAILABILITY (TONS PER YEAR)	ECONOMIC AVAILABILITY (TONS PER YEAR)
-	**HAUL ZONE TOTAL**	**CUMULA TIVE**	**HAUL ZONE TOTAL**	**CUMULATIVE**	**HAUL ZONE TOTAL**	**CUMULATIVE**
30-Minutes	610,339	610,339	307,244	307,244	35,323	35,323
60-Minutes	2,433,946	3,044,285	1,616,808	1,924,052	26,379	61,702
90-Minutes	3,913,513	6,957,798	2,705,374	4,640,726	8,653	70,355
120-Minutes	5,793,275	12,751,073	4,073,463	8,725,489	4,685	75,040

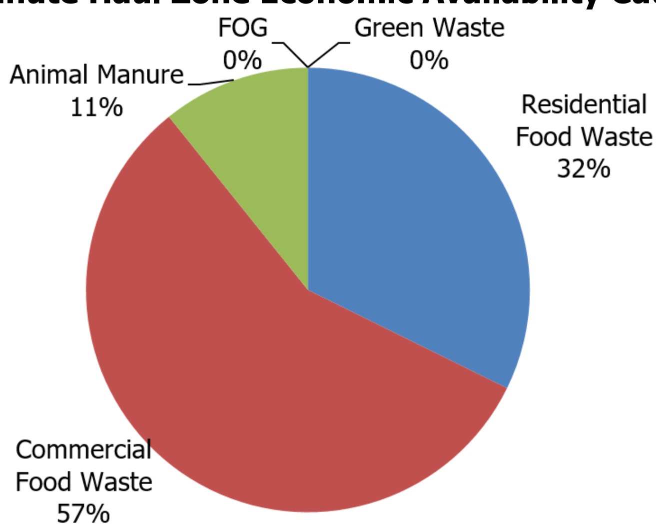
Source: TSS Consulting

	GROSS AVAILABILITY (TONS PER YEAR)	TECHNICAL AVAILABLITY (TONS PER YEAR)	ECONOMIC AVAILABILITY (TONS PER YEAR)
TOTALS	**12,751,073**	**8,725,489**	**75,040***

*After accounting for 160 tons per day (58,400 tons per year) demand from the three CleanWorld digesters.

Source: TSS Consulting

Figure 1: 60-Minute Haul Zone Economic Availability Categorization



Source: TSS Consulting

Incentives for Organics Diversion

At the time of preparation of this task report (Spring 2014), incentives for organic waste diversion were limited. TSS surveyed existing local food waste diversion programs and found the following prevalent incentives:

- Industry Sustainability Goals: The hospitality industry is a good example of an industry with strict sustainability standards and goals. The incentives for hotels are largely competition and customer preference.
- Marketing: Some local diversion programs have been incentivized by their ability to advertise to their client base (e.g. restaurants). Marketing incentives were largely individual value judgments made by managers or owners.
- Cost Savings: The most pervasive incentive was net cost savings. The majority, although not all, local diversion programs were incentives by a net cost savings to the business (e.g. food packaging facilities).
- Legislation: Assembly Bill 1826 (Chesbro, Chapter 727, Statutes of 2014)[16] (AB 1826) would require commercial source-separated organic waste recycling throughout the state. Beginning in April 2016, this bill would require a business that generates more than eight yards a week of organic waste to divert those organics from the waste stream. The threshold would decrease to two-yard customers by 2020.

Challenges to Implementation

The most significant challenge to collecting organic wastes is to modify existing infrastructure. Early obstacles include:

- Customer Economics: In a highly competitive market, it is challenging to provide additional recycling services in a cost-neutral manner or to find customers that are willing to pay extra for waste hauling.
- Franchise Agreements: Franchise agreements in the Sacramento area create highly competitive markets and limit the ability to change market dynamics. Franchise agreements with the County of Sacramento, the City of Sacramento, and the other incorporated cities in the SMUD service territory have made residential food waste collection particularly challenging without incurring significant additional costs.
- Route Density: With relatively low early-stage participation, food waste collection is typically more expensive than garbage or recycling collection due to drive times between pick-ups. This additional cost must be absorbed by the waste hauler or the customer.
- Education and Outreach: Even with willing participants, education and training to provide quality food waste feedstock takes time and effort increasing the costs to waste haulers.

---

16 AB 1826 passed in 2014 and was signed into law by Governor Brown.

Recommendations

While commercial and residential food waste feedstocks are approximately equal, existing infrastructure best supports the continued development of commercial food waste collection programs. Supporting CleanWorld's existing efforts to work closely with waste haulers to address early adoption challenges is critical to the continued development of this voluntary program.

The most significant advantage of AB 1826 is that it will allow waste haulers to charge for organics diversion services while remaining cost competitive, since organics diversion will be mandatory to commercial waste generators. The most significant challenge will be the contamination level of the potential AD feedstock product.

Regional Infrastructure Analysis

Food waste collection programs in the Sacramento Region are in the early adoption phase, which presents unique challenges for the path to full adoption and cost-effective implementation.

TSS found that green waste was prohibitively expensive to use in AD systems. Animal manure was identified as having limited potential for the Sacramento area ADs unless collocated with a dairy farm or feedlot. FOG is a viable option with the currently robust collection infrastructure. Food waste was identified as having the greatest potential for additional organic feedstock collection. The regional infrastructure analysis is therefore aimed at identifying the current practices for collection of pre-consumer and post-consumer organic food waste.

Current Infrastructure

At present, there is limited food and organic waste collection infrastructure available in the Sacramento region. With the development of the CleanWorld AD facilities in Sacramento and in Davis, the co-digestion facility at the Sacramento County regional WWTP, and composting facilities just outside of Sacramento, there has been increased interest by all of the regional waste haulers to develop strategies to effectively collect and divert organic wastes.

Nearly all of the food waste destined for the CleanWorld facility is collected and delivered by three solid waste haulers – Atlas Disposal, Republic Services, and Waste Management. These companies offer voluntary food waste collection programs, at additional cost, for their commercial clients. These haulers do not collect any residential waste, food or otherwise (with the exception of the pilot collection program being conducted by the City of Sacramento), residential hauling is under the purview of the City and County solid waste departments. The Sacramento Rendering Company is another facility in the Sacramento region that deals with a variety of pre-consumer and post-consumer food and organic wastes. However, much of what Sacramento Rendering Company is cooking oil grease, which has a commodity value as animal feed supplement and for producing biodiesel transportation fuel.

The City of Sacramento Recycling and Solid Waste Division instituted a pilot residential food waste collection program in April 2014. It consists of food waste collection from 900 homes in the Elmhurst district of Sacramento (the City currently services 124,000 residential customers with recycling and solid waste collection services). It is a voluntary program and will continue to March/April 2015.

Greenwise Joint Venture is a Sacramento-based regional non-profit organization focused on the concept of making Sacramento the greenest region in the country and a hub for clean technology. Greenwise has developed a pilot program to facilitate organic waste diversion for businesses and institutions in the Sacramento Region. This program is particularly designed to enhance feedstock delivery to the CleanWorld Sacramento facility, and is a component of the Sacramento area Farm to Fork to Fuel initiative.

The Green Restaurant Alliance of Sacramento (GRAS) is an organization dedicated to making Sacramento a leading sustainable food community. Its members include several restaurants in Downtown and Midtown Sacramento. Whereas it does not administer a food or organic waste collection program itself, GRAS assist various Sacramento restaurants with food waste diversion concepts and practices.

The Sacramento Clean Cities Coalition is a government-industry partnership designed to reduce petroleum consumption in the transportation sector. Clean Cities is currently funding outreach and training at local Sacramento schools to encourage the diversion of food waste from the garbage stream to use as feedstock in the CleanWorld SATS facility where it can be made into non-petroleum based transportation fuel.

Sacramento County (the unincorporated portions of the county) currently does not have a residential food/organic waste diversion and collection program nor are any pilot collection programs anticipated in near or medium future.[17]

Outside of Sacramento, several food waste collection programs have been developed in Northern California including Contra Costa County, Davis, San Jose, and San Francisco. Food collection programs can also be found in Seattle, San Diego, Eugene, New York, and Los Angeles and in many universities and national businesses.

Early Adoption Challenges:

- **Collection Density & Pick Up Routes**
  Collection density and routes are integrally connected and can be significant challenges to early adoption of food collection programs. Pick up routes must be optimized to minimize the fuel and time expenditure required to fill a collection vehicle to capacity. The length of a route directly correlates with the route's expense. Therefore, finding users with large volumes of food waste or small users in close proximity is important in reducing the cost of collection for the hauler.

---

17 Personal communication with Paul Philleo, Director, Sacramento County Department of Waste Management and Recycling.

- **Education and Training**
  Education and training is necessary to address systematic changes to waste disposal and to differentiate between sustainable disposal options. Systematic changes to waste disposal practices include identifying additional bin space and training users as to what material is acceptable for that waste stream. Training users (e.g., staff, students, customers) to use the correct method takes time, observation, targets, and audits to ensure that a specific program is effective.

- **Cost**
  Food waste diversion does not necessarily save the generators money. Even if the collection routes are subsidized by the haulers to the same price as garbage pickup, the food waste stream is very dense and does not take up a significant volume. While the weight of the garbage stream has been significantly reduced, the volume may not be. Since many generators pay by the bin (a volume measurement), their garbage collection may not actually be reduced. There is also a cost factor in training of employees to source-separate the food waste.

- **Space**
  Space constraints can be important both inside and outside of businesses. For hotels and restaurants that already maximize and optimize their space, finding room for another container inside loading docks and inside trash bin enclosures can be challenging. Many generators already have a garbage bins, recycling bins, and green waste bins. The addition of a few bins to an alley that already has many bins and is serviced by three different companies can cause congestion

- **Franchise System, Competitive Markets, and Institutional Constraints**
  Competitive markets, as discussed previously, create challenges with participation, routes, and collection density. The Sacramento area is a very competitive solid waste collection, transporting, disposing, and/or recycling of commercial wastes market. Commercial waste activities in the Sacramento Solid Waste Authority (SWA) jurisdiction are conducted by no less than 17 separate SWA franchised companies. Of these 17, three waste haulers, as previously discussed, conduct voluntary food waste collection and transport activities to the CleanWorld AD facilities.

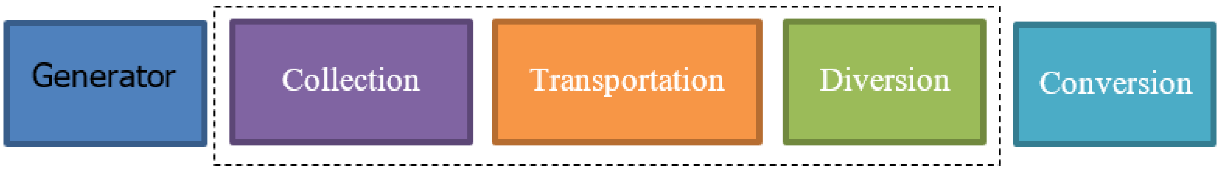
- **Odor**
  While garbage has always had odor concerns, food waste diversion in particular can cause serious odor and vermin issues if inappropriately handled. Food waste collection must occur at least once a week if not more frequently. Modifications to existing collection bins may be necessary to appropriately handle this high moisture content waste stream.

- **Anaerobic Digesters**
  Organic waste collection must be optimized to the available AD system. As AD facilities continue to be built, the specifications of the feedstock blend may be dynamic to meet new regional needs.

- **Economic Feasibility**

  The life cycle of food waste for the purposes of this study begins at the food waste-generating source. At the point of generation, the generator makes a decision to recycle the food waste or to continue with business-as-usual practice, including disposal in the garbage stream, land application, or composting. The life cycle is shown with the black dashed line in Figure 2.

Figure 2: Food Waste Life Cycle Schematic



Source: TSS Consulting

Collection, Transportation, and Diversion

Collection costs vary depending on the specific waste stream. However, the addition of food waste collection introduces another collection program with its concomitant additional costs. Another important aspect of collection cost is the level of source-separation. At this point, Sacramento does not have the infrastructure to effectively remove food waste from a standard unseparated waste stream. Therefore, feedstock must be at least partially source separated to meet pre-processing specifications at the CleanWorld facilities.

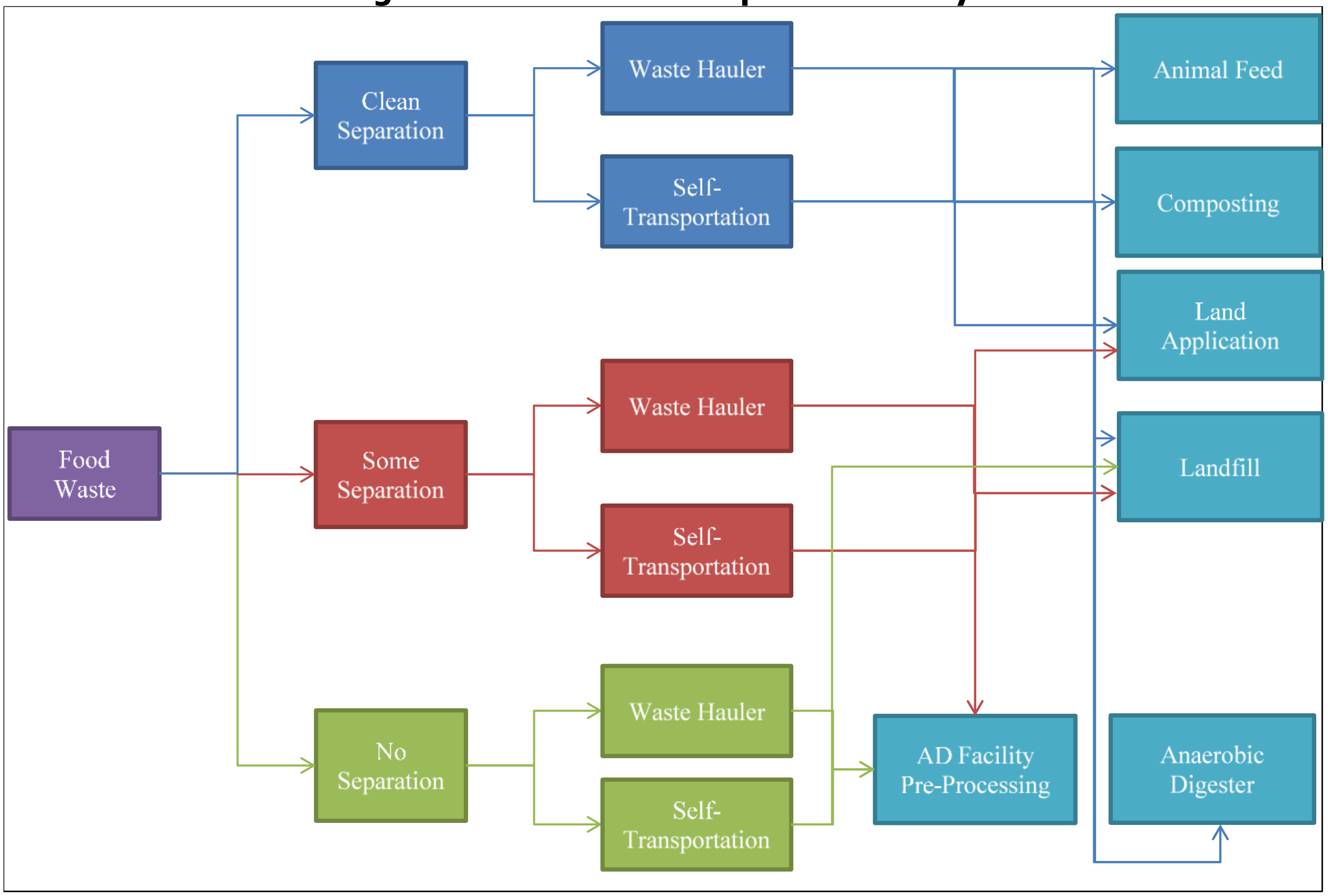
Transportation costs are a function of volume and drive time. Transportation costs can take on two forms: Distance to the disposal site (for all waste collection methods) and distance between pickups (for waste haulers). Transportation costs for different disposal options (AD, composting, land application, animal feed, and landfill) in the Sacramento region are relatively similar due to the central location of Sacramento. Each of these disposal options exists within economic haul distance of Sacramento. As waste haulers develop food waste collection programs, transportation costs are expected to decrease as collection density increases.

The cost of diverting food waste to an AD will vary by generator and waste stream composition. The potential for generator savings depends on the alternative diversion or disposal method.

Life Cycle Cost Analysis

For the purposes of this economic feasibility study, the food waste collection life cycle has been identified into three pathways based on levels of source-separation (Figure 3).

Figure 3: Food Waste Disposal Pathways



Source: TSS Consulting

Animal feed is typically the best use for clean source-separated food waste and typically has the greatest economic potential. Composting and land application currently have comparable end uses based on price. With low capital costs associated with these disposal options, disposal rates are relatively attractive. Landfill disposal is typically the highest cost disposal option and can accept any type of food waste. Table 2 shows representative costs for disposal options throughout Northern California.

Table 2: Representative Disposal Costs in Northern California

Disposal Option	Acceptable Feedstock Types	Costs
Animal Feed	Clean Separation	-$5 to $10 per ton*
Composting	Clean Separation Some Separation	$0 to $10 per ton
Land Application	Clean Separation Some Separation	$0 to $10 per ton
Landfill Disposal	Clean Separation Some Separation No Separation	$25 to $120 per ton
Anaerobic Digestion	Clean Separation Some Separation No Separation	$0 to $35 per ton**

Table Notes:

*   A negative value indicates that a generator is paid for the clean food waste.

**   Includes a range of ADs in Northern California and not only prices charged by CleanWorld.

Source: TSS Consulting

In addition to disposal costs, food waste generators incur collection, transportation, and liability costs. These costs vary greatly by waste generator and food waste type. For an AD to capture a particular food waste, the life cycle cost of waste disposal, including collection, transportation, liability, and disposal fees, plus potential public relations benefits, must be a cost-effective opportunity for the generator.

While the economics vary by food waste generator, TSS suggests that for the pilot project, SMUD consider food waste sources currently going to the landfill. This type of generator is likely to have a relatively high disposal costs and best represents the type of food waste generator that is not already managing and collecting their food waste.

Biogas Potential

The immediate biogas potential for a pilot project depends on the selected project participant. The demonstration project will assess different methods to cost effectively capture waste streams from food waste, green waste, FOG, and animal waste. Based on the CleanWorld technology, biogas yields from these waste streams are identified in Table 3.

Table 3: Biogas Yield Potential by Waste Stream

Waste Stream	Biogas Yield[18]	Biogas Energy Content
Food Waste[19]	4,108 ft^3/ton	745 Btu/ft^3
Green Waste	2,897 ft^3/ton	561 Btu/ft^3
FOG[20]	11,207 ft^3/ton	652 Btu/ft^3
Animal Manure	1,779 ft^3/ton	614 Btu/ft^3

Source: TSS Consultants

Using the values from Table 3, Table 4 shows feedstocks with technical and economic potential in the Sacramento Region (less existing demand).

18 Based on 25 percent solids.

19 Zhang, Ruihong and Joshua Rapport. (University of California, Davis). 2011. Anaerobic Phased Solids Digester Pilot Demonstration Project. California Energy Commission. Publication Number: CEC-500- 2013-077.

20 Zhang, R., Romano, R., Chen, X., Kim, H. (University of California, Davis). June 30, 2007. Anaerobic Co-Digestion of Grease Trap Waste and Dairy Manure & Zhang, R., Romano, R., Chen, X., Kim, H. (UC Davis). June 30, 2007. Anaerobic Digestion of Selected Food Waste Streams. SMUD.

Table 4: Cumulative Biogas Potential in by Haul Zone Northern California

Waste Stream	Potential Type	30-Min MMBtu/yr (MWh_{th}/yr)	60-Min MMBtu/yr (MWh_{th}/yr)	90-Min MMBtu/yr (MWh_{th}/yr)	120-Min MMBtu/yr (MWh_{th}/yr)
Food Waste	Technical	212,695 (62,337)	676,541 (198,283)	1,192,376 (349,465)	1,646,218 (482,479)
Food Waste	Economic	97,894 (28,691)	178,358 (52,282)	204,790 (60,020)	219,087 (64,211)
Green Waste	Technical	106,278 (31,148)	241,801 (70,868)	448,775 (131,528)	681,024 (199,597)
Green Waste	Economic	0 (0)	0 (0)	0 (0)	0 (0)
FOG	Technical	107,643 (31,548)	244,907 (37,778)	298,424 (87,463)	369,110 (108,180)
FOG	Economic	0 (0)	0 (0)	0 (0)	0 (0)
Animal Manure	Technical	208,557 (61,125)	1,734,984 (508,495)	4,378,998 (1,283,411)	8,506,401 (2,493,084)
Animal Manure	Economic	3,540 (1,037)	3,540 (1,037)	3,540 (1,037)	3,540 (1,037)
Total	**Technical**	**635,173 (186,158)**	**2,898,233 (849,424)**	**6,318,573 (1,851,868)**	**11,202,753 (61,058)**
Total	**Economic**	**101,434 (29,729)**	**181,925 (53,319)**	**208,329 (61,058)**	**222,626 (65,248)**

Table Note: The top line of each row shows energy potential in terms of British Thermal Units while the bottom, parenthetical lines show energy potential in terms of electric power.

Source: TSS Consultants

Pilot Project Planning

The pilot project planning process focused around stakeholder outreach to identify effective and pertinent pilot projects that would enhance the collection of food waste in the Sacramento region. Based on the findings, the Sacramento region is host to a number of pilot-scale food waste collection programs. Each of the three major haulers serving Sacramento, Atlas Disposal, Republic Services, and Waste Management, have begun implementing pilot commercial food waste collection programs with strategic client partners. The Sacramento Hotel Association and the GRAS are leading the development of industry-specific food waste resource management. Additionally, the City of Davis (about 20 miles west of Sacramento) has piloted food waste collection in local schools, the City of Sacramento has conducted a residential food waste collection program, and the University of California (U.C.) at Davis is successfully collecting campus food waste as feedstock for the CleanWorld Renewable Energy Anaerobic Digestion facility, located at the U.C. Davis landfill.

The greatest barriers facing food waste generators are education, collection costs, and implementation costs (e.g., staff training). Successful programs to develop food waste collection will address the challenges that food waste generators face when deciding whether to switch to food waste diversion. Education and training are important tools to provide food waste generators to reduce the risk associated with the business decision and increased participation will help reduce collection costs as the waste haulers achieve economies of scale.

Stakeholder Meeting

An open-forum stakeholder meeting was conducted on July 15, 2014 to develop a better understanding of the challenges with food waste collection and the opportunities for SMUD to assist in the growth of the industry. The stakeholder meeting was organized to vet the findings identified in Task 2. Attendees came from a variety of sectors, such state and local government, educational facilities, hotel/restaurants, event facilities, community organizations, utilities, and waste hauling companies.

Food Waste Collection Challenges

The stakeholder group was asked to discuss specific challenges that they have identified in their efforts to establish and promote a food collection system. Some stakeholders have established food collection programs while other stakeholders had interest, although their programs are in their infancy. Challenges identified are:

Acceptable Levels of Contamination - Waste generators are often uncertain about what are considered acceptable levels of contamination for food waste collected.

Bins & Containers - Selecting the appropriate size bin for different rooms is a challenge for start-up operations. Bins for food waste need to be leak-proof to maintain site cleanliness.

Co-mingling v. Source Separation - Particularly for residential generators, co-mingling organic wastes into a single container will be important to take advantage of existing collection infrastructure.

Composting vs. Anaerobic Digestion - Understanding the operational differences between composting and ADs is important to the successful implementation of food waste collection programs.

Employee Participation - Employees are not accustomed to separating food waste from traditional recycled material. Training is paramount.

Industry Standards - At this point, informational material varies between waste haulers and agencies trying to promote food waste collection. Industry-wide standards and generic labeling are needed.

Project Champion – Successful programs have internal project champion who should be supported by both management and other employees.

Roadmap/How-To - The average food waste generator does not know the details about how to effectively and efficiently start a food waste collection program. A roadmap or "how-to" guide would be beneficial.

Space - Some waste generators have struggled to identify space for additional food waste collection bins. Bin enclosures and alleys can have space constraints to adding additional bins or totes.

Training - Training and education was identified as the single most critical ongoing factor for project success. Continual reinforcement of the training is necessary.

Waste Removal - Food waste generates more odors and leave greater residue in containers. Food waste collection systems must be able to address cleaning the bins to minimize odor and maximize cleanliness.

Potential for SMUD to Assist

The stakeholder group was also asked to identify ways in which SMUD could participate and assist in the development of food waste collection programs. These included:

Sector-Specific Food Waste Program Roadmaps - Participants unanimously agreed that each commercial food waste collection program would be unique to each business type. Providing high-level, industry-specific pathways to developing collection programs would reduce the startup risk.

Business Kits - SMUD could provide kits to business with the basics to get collection projects going. These kits would include items like bins, bags, signage, and educational material.

Capital Infrastructure Investment - SMUD can provide funds to continue to develop the infrastructure for food waste collection systems including sorting facilities, bins, and trucks.

Champion Food Waste Diversion - SMUD can be the project champion for businesses that do not have their own internal champion. The respect that SMUD commands in the Sacramento area puts SMUD in a unique place to act as a project champion and move diversion projects forward.

Early Involvement - As development continues in Sacramento, SMUD has the unique opportunity to be involved in the early-stage planning of these facilities. SMUD can use their position in the community to influence development design to include food waste collection.

Education/Training - Providing educational materials and training support for project champions at local businesses would support the development on individual programs.

Host Meetings to Spread Awareness - SMUD has the ability to gather high-level decision makers in the Sacramento region. SMUD has the opportunity to use this unique ability to promote food waste collection with the true decision makers in large businesses around the area.

Incentives -SMUD could offer incentives (e.g., reduced electricity rates) for SMUD customers that participate with a food collection program to help offset some of the startup costs.

Marketing/Community Outreach - Participants perceived SMUD's marketing arm to be particularly effective and influential in the Sacramento region.

Resource Database - SMUD can serve as a one-stop shop for resources and informational material for food waste collection information.

Pilot Project Development

Based on the feedback received during the July 15, 2014 stakeholder meeting, TSS recommended a multi-faceted procurement strategy to enhance regional food waste collection. This strategy included:

Targeted Feedstocks – Local business and institutional enterprises that serve food, including hotels and restaurants, schools and other educational facilities, large public employers with cafeteria operations, hospitals and other large institutions.

Education, Outreach, and Training - Informational materials (e.g., posters, stickers, FAQ, training videos) to assist in standardizing food waste collection information. In collaboration with the participating organization, develop a monitoring and training program to increase program participation and diversion rates.

Marketing and Promotional Incentives - Promotional materials (e.g., stickers, table-top fliers) that business can use to promote their sustainable initiatives. Develop community outreach plan to disseminate information about the pilot program and to keep participants informed about the success of the program.

Potential Pilot Project Participants

TSS, in collaboration with SMUD and the Sacramento-area waste haulers, identified preferred organizations for a pilot program**.** Organizations were identified by their business type and a representative facility was selected:

- Airport: Sacramento International Airport (SMF)
- College/University (4-year): Sacramento State University
- Event Center: Sacramento Convention Center
- Government Office: Franchise Tax Board

- School: River City High School
- Hospital: U.C. Davis Medical Center
- Mall: Arden Fair Mall
- Sports Arena: Raley Field (River Cats)

Hotels and grocery stores were excluded from the list as TSS found that many of the prominent Sacramento-area organizations were already engaged in food waste diversion.

TSS, along with SMUD, identified five selection criteria (with weighting factors) to evaluate the potential for a pilot project. The rankings based on the criteria are shown in Table 5. These five criteria were:

- Local Replicability (30 percent)
- Direct Community Interaction (25 percent)
- Scheduling (20 percent)
- Resource Potential (15 percent)
- Pre-Consumer/Post Consumer Food Waste Characterization (10 percent)

Table 5: Project Participant Ranking

Site Name	Ranking	Score (of 3)	Percentage Score
College/University: Sacramento State University	1	2.30	76.7
Airport: Sacramento International Airport	2	2.05	68.3
Grade School: River City High School	3	2.00	66.7
Hospital: U.C. Davis Medical Center	4	1.85	61.7
Government Office: CA Franchise Tax Board	5	1.75	58.3
Mall: Arden Fair Mall	6	1.50	50.0
Event Center: Sacramento Convention Center	7	1.25	41.7
Sports Arena: River Cats	8	0.65	21.7

Source: TSS Consultants

TSS worked with Sacramento State University to develop a pilot program on site. After one month of coordination, a pilot program could not be developed to meet the timing needs of the SMUD, CleanWorld, and Argonne National Labs and the schedule designated in the CEC grant. TSS shifted focus to SMF and continued to work with the regional waste haulers to develop pilot programs.

Selected Pilot Programs

SMF was selected as an ideal candidate for a food waste collection pilot project working with existing food vendors to enhance the collection of source-separated food waste. A pilot program at SMF offers the potential to be replicated at food courts across the Sacramento region, including malls, schools, and businesses.

The SMF pilot program will focus on pre-consumer food waste generated by airport food vendors. SMF provides a streamlined process for food waste collection as the airport infrastructure allows for waste and recycling disposal to be aggregated and collected by one waste hauler. The pilot project will focus on staff training to develop a new systemic framework for waste disposal.

As also identified in the July 15th stakeholder meeting, lack of education is a significant challenge facing business owners as they decide whether to adopt and implement a food waste collection program. The waste hauler pilot program was developed to address the need for additional education for a large number of Sacramento-area food waste generating facilities. Atlas Disposal and Republic Services, as active participants in the pilot project planning process, have agreed to participate in a pilot program.

Pilot Project Implementation

Sacramento International Airport Pilot Project

As part of the project, SMF is testing and analyzing pre-consumer food waste collection and diversion activities at participating restaurants in Concourse B. Food waste collected through this program will be diverted away from landfill disposal and directed to CleanWorld A in the Sacramento area. Even with the conclusion of the SMUD project, SMF continues with their food waste collection and diversion activities.

In the fall of 2014, SMF adopted a formal recycling policy. Through this policy, SMF initiated a comprehensive recycling program to improve operational sustainability, reduce waste to landfills, and reduce waste management costs. SMF is interested in expanding its recycling program to include organics. A pilot project was developed to test the potential for pre-consumer food waste diversion at participating restaurants within Concourse B. Goals of the pilot project include:

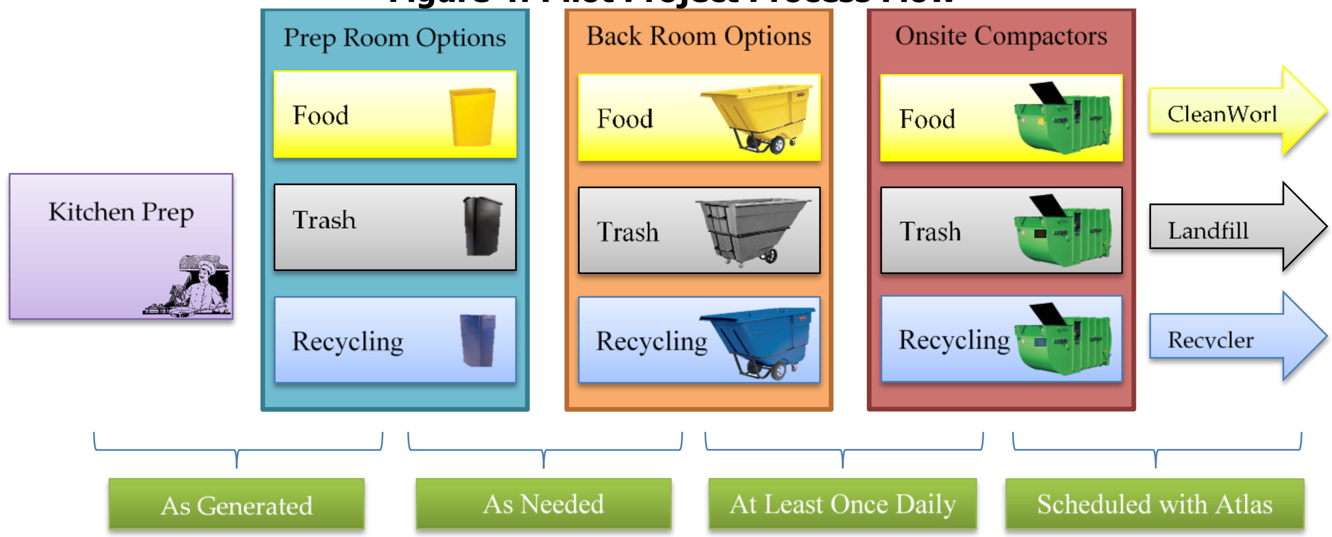
- Minimize waste sent to landfills;
- Enhance SMF's image as good stewards of the environment;
- Expand upon current recycling programs;
- Reduce overall costs of waste management; and
- Prepare for the implementation of AB 1826.

SMF Food Waste Collection Pilot Project Implementation

SMUD assisted this pilot program with equipment funding, hauling costs, and reporting pilot project results within this report. Although SMF continues with the pilot project and looks to develop expanded food waste collection for the entire airport, this report presents results from the initial roll-out. The pilot project operated for two months in early 2015.

The pilot project restructured waste management practices at the participating restaurants in Concourse B. Baseline waste management practices included recycling and trash. Gray containers were used for both trash and recycling. As needed, the trash and recycling were taken out from the preparation area and dumped into gray tilt trucks. The gray tilt trucks were emptied into compactors daily. The demonstration project modified the existing system as shown in the process flow diagram in Figure 4.

Figure 4: Pilot Project Process Flow



Source: TSS Consultants

As shown in Figure 4, the pilot project collects three unique waste streams. The demonstration project required the purchase of new waste collection bins including 15-gallon Slim Jim trash cans in the kitchens and one cubic yard tilt trucks for waste aggregation in the back hallways for delivery to the trash compactor. Slim Jims and tilt trucks are color coordinated with gray for landfill, blue for recyclables, and yellow for food waste. Each participating restaurant was provided separate food and recycling Slim Jims and tilt trucks. The restaurants' existing gray Slim Jims and tilt trucks were converted to trash-only.

One of the two trash compactors at Concourse B was converted to a food waste compactor, leaving one compactor for trash and one for recycling.

SMF Staff provided training to participating restaurant employees and managers (both morning and afternoon shifts). Staff training comprised of a presentation using laminated slides, live demonstrations, and participant tests. The training presentation discussed the importance of landfill diversion, described the new system to be implemented at the airport, and an overview of how the CleanWorld AD technology works. Restaurant staff that participated in the training was incentivized to participate in the tests with small prizes including gift cards and reusable beverage containers.

SMF Pilot Project Results

Over the course of this pilot program, the food waste compactor was removed from Concourse B twice and the contents were delivered to and accepted by CleanWorld. The food waste was delivered to the CleanWorld facility at the SATS for processing into a slurry acceptable to their AD system (see Table 6).

Table 6: SMF Pilot Program Results

	Date	Tonnage	Number of Days Collected	Number of Participating Restaurants	Average Daily Collection (lb/day)	Average Daily Collection (lb/day/ Restaurant)
Food Waste Pick Up 1	1/30/2015	3.2	10	6	634	106
Food Waste Pick Up 2	2/24/2015	5.9	18	6	652	109
Total		**9.1**	**28**	**6**	**646**	**107**

Sources: TSS Consultants

Lessons Learned from SMF Pilot Project

Although the pilot project duration with SMUD involvement was relatively short due to contractual time frames, however, SMUD and its consultant, TSS, was involved long enough to capture several lessons learned. These included:

Increased Recycling - Through the deployment of the organics diversion program, SMF staff observed significant increases in recycling materials and decreases in landfill-bound trash.

Tilt Truck Sizing The existing program uses one-yard tilt trucks for food, recycling, and trash waste aggregation. Despite the color coordination, there were still challenges, particularly at the onset of the program with improper utilization of the tilt trucks.

Slim Jim Quantities and Size – Adequate number and appropriate placement of food waste Slim Jims is necessary.

Convenience is Critical – Kitchen staff is very participatory in food waste segregation, but support staff may not be. Space constraints for new food waste collection bins and movement of additional bins to compactors was an issue.

Monitoring - Program monitoring and compliance is critical. There is a strong correlation between number of trash patrols and compliance with the new system.

Labeling Only Goes So Far, In-Person Communication is Critical - Both signage and training of all personnel handling waste, whether it be food or non-food is necessary.

Odor Mitigation - Food handling is an important aspect of odor management. Because the food waste was processed by a depackaging system at CleanWorld, bagging the food waste is okay and should be done as it controls odors significantly.

Interest in Sustainability - Overall there was a positive response to the pilot program. Many of the managers and staff understand the importance of diversion from a global perspective and want to do the right thing. In-house champions were critical to early adoption and project success.

Variations in Staff Participation - A particular challenge for program implementation has been how to engage apathetic employees who do not seem to care about sustainable practices and diversion.

Underestimated Training Requirements - The original training plan underestimated the amount of training required. Restaurants have a high number of part-time and shift employees resulting in a larger total number of employees that are rarely in one room together.

Waste Hauler Pilot Project Implementation

As part of pilot project component of this study, Atlas Disposal and Republic Services conducted waste characterizations and impact assessments on a total of 200 customers (100 by each hauler) to identify the potential to implement food waste collection programs and to identify the economic impacts of implementing the program.

Pilot Project Goals

This pilot project sought to develop a better understanding of the potential food waste resource from commercial generators and to gather real-time data for the haulers to improve their existing food waste collection efforts. The pilot project addressed early adoptions challenges identified in Regional Infrastructure Analysis including:

- Collection density & pick up routes
- Education
- Cost

Information about food waste in the commercial municipal solid waste stream is relatively limited, but also has the greatest potential to increase regional food waste collection and diversion. The intent of the pilot project with the waste haulers was not to provide in-depth waste characterization information in a statistically significant sample size, but instead to provide preliminary data based on observations that can be used to guide further development of food collection programs in the Sacramento area.

Hauler Pilot Project Implementation

Implementation of the pilot projects consisted of two primary components: A waste characterization of 100 customers each that were considered high priority for near-term food waste collection; and an assessment of the potential customer impacts from food waste collection.

The waste characterization consisted of conducting a site visit to each customer and surveying their containerized trash to estimate the amount by volume and mass of the wet organic fraction of their trash. The trash characterization information was used to identify potential customer impacts, such as:

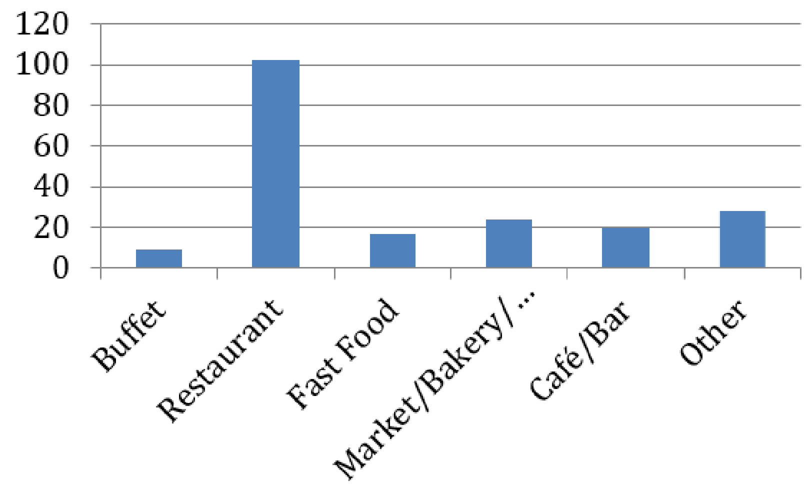
- Will the customer be able to reduce trash pickups?
- Will the customer be able to increase recycling?
- Logistics as to bin size and frequency of pickups;
- Estimated cost for food waste diversion, and;
- Conversion to food waste collection potentially during the pilot project.

Pilot Project Results

As high priority customers were targeted for the pilot project, the sample was heavily weighted to the food service industry. Table 7 graphically displays the 200 high-priority customer classification distribution.

Table 7: Customer Classification Distribution

Classification	Count
Buffet	9
Restaurant	102
Fast Food	17
Market/Bakery/Deli	24
Café/Bar	20
Other	28
Total	**200**



Source: TSS Consultants

Contracted waste volume was an important consideration with the pending requirements of AB 1826, which mandates businesses generating a specified amount of organic waste per week to arrange for recycling services for that organic waste. The businesses covered by AB 1826 increase over a four-year period as follows:

- April 1, 2016 – All businesses that generate eight cubic yards or more of organic waste
- January 1, 2017 – All businesses that generate four cubic yards or more of organic waste
- January 1, 2019 – All businesses that generate four cubic yards or more of commercial solid waste
- January 1, 2020 – All businesses that generate two cubic yards or more of commercial solid waste

Based on volumetric waste determined during the waste characterizations, Table 8 shows the percentage of surveyed customers who will be impacted by AB 1826 due to the volume of food waste generated.

Table 8: Percentage of Business Affected by AB 1826

Regulatory Year	Overall	Buffets	Restaurants	Fast Food	Market/ Bakery/Deli	Café/Bar	Other
2016	5	22	3	0	13	5	4
2017	19	78	18	18	13	15	14
2019	71	89	72	88	58	55	71
2020	99	100	98	100	100	100	100

Source: TSS Consultants

Note that the 2020 implementation will take effect only if CalRecycle determines disposal of organic waste has not been reduced to 50 percent of the level of landfill disposal during 2014. Organic waste is defined as food waste, green waste, landscape and pruning waste, nonhazardous wood waste, and food-soiled paper waste that is mixed with food waste.

In the collection of the waste characterization data, it was noted that the distribution of food waste by mass varied considerably from the food waste percentage by volume. The other constituents of the waste stream significantly impacted the mass fraction determination. For example, a bin comprised of 20 percent food waste by volume and 80 percent non-broken down waxed cardboard (commonly used in cardboard boxes containing fresh produce) would result in a relatively high mass fraction estimate while a bin comprised of 20 percent food waste by volume and 80 percent non-recyclables by volume would result in a substantially lower mass fraction estimate. A matrix comparing food waste mass fractions and volumetric fractions is shown in Table 9.

Table 9: Distribution Matrix of Assessed Mass and Volume Fractions

		Volume Fraction	**Volume Fraction**	**Volume Fraction**	**Volume Fraction**	**Volume Fraction**	**Volume Fraction**
		0% - 20%	20% - 40%	40% - 60%	60% - 80%	80% - 100%	**Total**
Mass Fraction	0% - 20%	51					**51**
Mass Fraction	20% - 40%	40	3				**43**
Mass Fraction	40% - 60%	7	35				**43**
Mass Fraction	60% - 80%		27	19			**46**
Mass Fraction	80% - 100%		2	9	5	2	**18**
Mass Fraction	**Total**	**98**	**67**	**28**	**5**	**2**	**200**

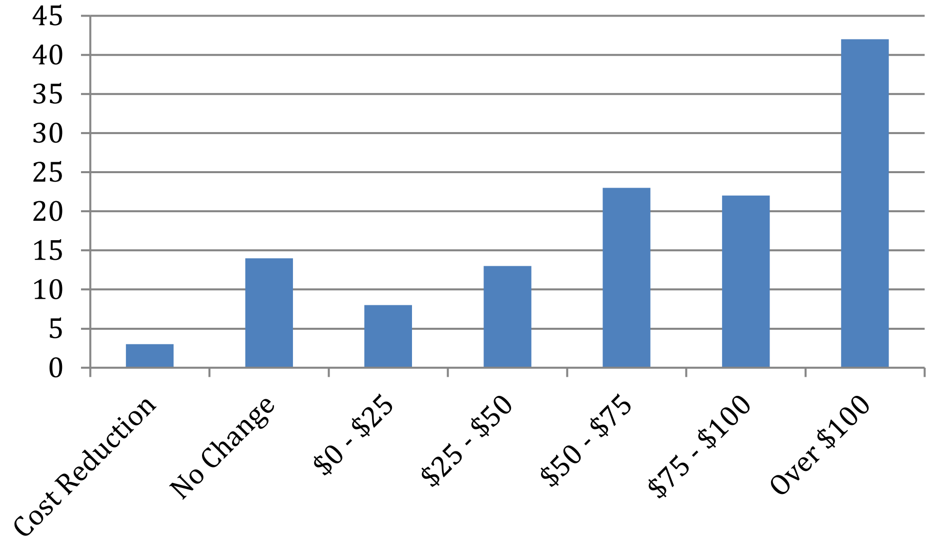
Source: TSS Consultants

Based on the waste characterization, the pilot program haulers estimated the types of food waste collection service that they might offer their customers. Of the 200 customers surveyed, 75 could not effectively implement a food waste collection system due to low food waste volumes and/or space constraints. This is an important finding when evaluating the potential to develop food waste collection programs in the future. The customers surveyed in this study represent a select group of high-potential customers, yet almost 38 percent of those surveyed could not implement a food waste collection program.

TSS analyzed the remaining 125 customers to determine cost estimates for the food waste program logistics, the potential for increased recycling, and the potential for decreased trash volumes. The distribution of estimated monthly costs is shown in Table 10.

Table 10: Estimated Cost of Implementing a Food Waste Collection Program

Monthly Costs	Count
Cost Reduction	3
No Change	14
$0 - $25	8
$25 - $50	13
$50 - $75	23
$75 - $100	22
Over $100	42
Total	**125**



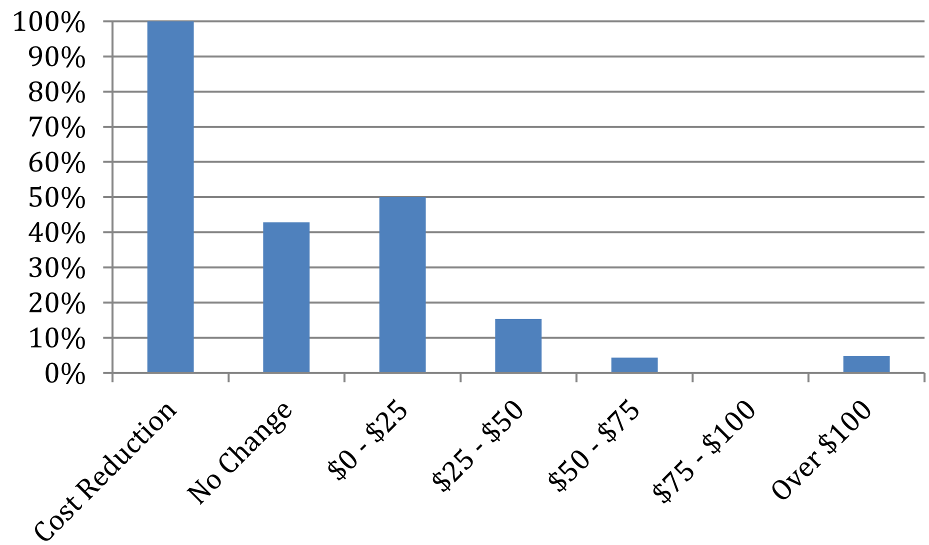
Source: TSS Consultants

Generally, food waste collection programs increase costs for the customer. TSS identifies costs to be a barrier to the widespread adoption of food waste collection programs.

During the 3-month pilot project, 18 customers converted to food waste collection. Table 11 illustrates the shows the percentage of customers who converted to food waste collection programs in each cost category during the pilot study.

Table 11: Estimated Cost of Implementing a Food Waste Collection Program

Monthly Costs	Count
Cost Reduction	100%
No Change	43%
$0 - $25	50%
$25 - $50	15%
$50 - $75	4%
$75 - $100	0%
Over $100	5%



Source: TSS Consultants

Notably, all of the customers offered a cost reduction converted to a food waste collection program, suggesting the importance of cost in a business decision. However, more than half of the customers offered no change in monthly cost or a $0 - $25 per month increase did not convert during the project period. Observations from the Haulers indicate that these decisions are based on a wide range of factors including space and work associated with implementing a new system.

Lessons Learned

Lessons learned were reported through comments in the waste characterizations and impact assessments and in interviews with the haulers after the pilot program was completed and include:

Space Constraints – many customers have space constraints for additional bins needed for food waste collection.

Recycling Needs Improvement – many customers are currently not recycling to full capacity, suggesting it will take several years to develop effective source-separation habits.

Language Barriers - In several locations, there was a significant language barrier that hindered effective communication about food waste diversion.

Fast Food & Take Out Discarded Little Food Waste - The haulers observed that fast food and take out facilities were generally not good sources of food waste as they tend to be efficient with food preparation and food is consumed offsite.

High End Restaurants Had Relatively Clean Food Waste - These restaurants appeared to have greater amounts of food waste, likely due to the use of fresh ingredients and higher priced food allowing for more selective food use.

Geographic Clusters - Haulers found several clusters of food waste generators. This information is valuable for assessing potential lower cost food waste routes.

De-Packaging is Essential - No waste characterizations revealed perfectly clean food waste; therefore the ability to remove contamination

Larger Volume Food Throughput Resulted in Less Food Waste - The larger volume of food throughput generally corresponded to a lower volume of food waste. This was found in fast food facilities and in large food processors. The more food throughput, the greater the operational cost is relative to total operations, thus greater efficiency is needed resulting in less food waste.

Significant Managerial Opposition - The haulers encountered significant opposition to food waste diversion programs due to the increased operational challenges including extra bins and staff training.

Markets Change by Jurisdiction - Within the Sacramento area are many jurisdictions, with each jurisdiction has different rules making it challenging for a uniform food waste collection program in the area.

Customer Cost Is a Driving Influence - Cost was the most noted reason for disinterest in food waste collection programs.

Biomass and Biogas Potential

Using estimates from the waste characterizations above, the gross potential of food waste available from the 200 customers was estimated to be 243.7 tons per week. Removing the 75 customers that could not implement a food waste collection program reduces the technical potential of 209.8 tons per week. For the economic potential, the conversion rates identified in Table 12 were used to estimate a total of 36 tons per week. Actual conversions are estimated to be 18 tons per week of food waste collection. Biogas potential is calculated based on 6,500 scf per year per ton of food waste and GHG savings are calculated based on food waste diversion from landfill based on the High-Solids Anaerobic Digestion Low Carbon Fuel Standard pathway used by CleanWorld for Low Carbon Fuel Standard credits.

Table 12: Biomass and Biogas Potential

	Gross Potential	Technical Potential	Economic Potential	Actual Conversions
Tons per Week	243	210	36	18
Tons per Day	35	30	5	2
Tons per Year	12,708	10,942	1,867	961
Biogas Potential (MMscf/yr)	82	71	12	6
GHG Savings ($MTCO_2e$/yr)	5,808	5,000	853	439

Source: TSS Consultants

Recommendations/Next Steps

Although the SMUD biogas project with CleanWorld and Argonne National Laboratory ends on March 31, 2015, there will be the continuing need for food and organics diversion and collection, particularly in the commercial sector per the pending implementation of AB 1826. With AB 1826 mandating a progressive implementation of the commercial sector up to the year 2020, it is up to the Sacramento area solid waste agencies (and agencies in which solid waste collection is administered to ensure that the basic tenets of AB 1826 are established.

The principal recommendation would therefore be that the commercial sector, as nearly all will captured by AB 1826 diversion and collection requirements by 2020, be kept advised by both the appropriate local agency and the waste haulers with commercial accounts. AB 1826 does further mandate that local solid waste agency jurisdictions also implement an organic recycling program. The Sacramento Regional SWA, which consists of the City of Sacramento and the unincorporated area of Sacramento County, is already embarking on developing this plan.

The Project Team recommends that the SWA, during implementation of their AB 1826 organics management program, carefully consider the lessons learned highlighted above. Paramount in the SWA program should be targeted education/outreach to the affected commercial sectors over the next five years. This should further be encouraged for the other local jurisdictions and their respective AB 1826 plans.

In identifying generators of commercial organic waste, SWA and the other jurisdictions should assist in setting up food and organic waste diversion and collection programs at the various large business and commercial campuses (e.g. Intel, Hewlett Packard, VSP, etc.), academic facilities (e.g. Sacramento State University, McGeorge School of Law, etc.), hospitals, and the myriad of local and state government buildings located throughout Sacramento County.

The Project Team also recommends that the SWA and other local jurisdictions consider Valley Vision's current efforts in developing implementation strategies for using food waste in the Sacramento area as feedstock for renewable fuels and clean energy[21].

Communication and Outreach

To promote the findings of the biogas resource assessment, procurement, and pilot collection program study, TSS has compiled a set communication and outreach materials in collaboration with the various project partners.

21 Valley Vision Website: https://valleyvision.org/projects/rico-supporting-clean-technology-sacramento-region/

CHAPTER 2: Bench- and Pilot-Scale Digester Tests at Argonne National Laboratory

Introduction

The goals of Task 3 are to scale up the process to pilot-scale experiments (from 10 liters (L) to 100's of liters) and operate for six months. A variety of factors that affect the rate of digestion and biogas production were evaluated during this work. These include pH, biochar to solids ratio, carbon/nitrogen ratio, mixing of the digesting material, the particle size of biochars, and the retention time. Methane gas production rates were accelerated by the addition of trace nutrients, such as nickel, cobalt and iron. The accumulation of silica and other impurities were also monitored in the digester environment.

The following activities were successfully completed:

- Designed and operated pilot-scale digesters (10 L – 100's L) considering the utility partners' anaerobic digesters criteria.
- Determine replenishment rate of mineral carbonation material in the digester.
- Monitor struvite ($MgNH_4PO_4 \cdot 6H_2O$) formation in the digester – Not completed, olivine rocks were removed from the experiment, reducing the need to monitor struvite formation in the digester. The project team decided to use biochar instead of olivine in the digesters on July 25, 2014. The CEC Project Manager was also present in this meeting.
- Investigate impact of byproducts on reaction chemistry and digester microbial populations.
- Determine methane yield (volume of CH_4 per amount of volatile solids (VS) added to the system).

Argonne's deliverable for this task includes daily biogas production, biogas yield, methane yield, and CO_2 production. These were monitored in batch and in two different scale experiments in a two-stage semi-continuous configuration (0.5 L and 14 L). In both semi-continuous experiments, the walnut biochar was added to the second stage methanogen digester at a 6 g biochar/ 10 L loading rate where the percent methane was statistically higher for all of the test conditions by a mean difference of 10 percent. The methane yield was approximately 550 mL CH_4/g VS_{added} for both the bench scale and pilot scale semi-continuous experiments.

There was no statistical difference in the methane yield for the walnut supplemented digesters compared to the control digesters leading to the conclusion that there was no impact of the walnut biochar addition on the anaerobic digester microbial community structure and dynamics. In fact, the biochar seems to enhance growth of methanogenic microbial community in the digesters since biochar-supplemented digesters had approximately 1.5 times the relative abundance of Euryarchaeota compared to the control. More importantly, the walnut biochar sequestered approximately 38 percent of the CO_2 produced compared to the positive control. This resulted in a 1.75 times reduction in the volume of CO_2 produced in the bench scale digesters and a 3.3 times reduction in the pilot scale digesters.

Materials and Methods

The AD experiments were run using food waste as the substrate and sewage sludge as the inoculum source. Based on recommendations from Clean World, the food waste was collected from home and consisted of approximately 11 percent fat, 6 percent carbohydrates and 83 percent vegetable matter. Food waste was used in these experiments to best simulate the operating conditions and feedstock composition used at the field demonstration at Clean World's ARP plant. Table 13 shows the chemical analysis of the food waste. The food waste was then diluted using deionized water to obtain the desired organic loading rate (OLR). The sewage sludge was provided by Woodridge Greene Valley Wastewater Facility located at Woodridge, IL. Pure sewage sludge was also tested using olivine instead of biochar.

The Woodridge facility operates a temperature-phased anaerobic digester system for sludge treatment, consisting of two digesters in sequence in order to separate acid and methane formation stages of the AD process. The first digester (acid phase) is operated at mesophilic temperature (~37 °C) with hydraulic retention time (HRT) of 1.2 days, and the second (methane phase) digester is operated at thermophilic temperature (~53 °C) with HRT of 12 days. The inoculum was obtained from both the acid-phase digester and the methane-phase digester to simulate operating conditions at the ARP's digesters. Walnut biochar samples were provided by Dixon Ridge Farms located on Putah Creek Road in Winters, California (Near the U.C. Davis Campus).

Table 13: Analysis of Food Waste Substrate

Parameter	Value
Moisture content (%)	87.6%
Volatile Solids (VS) (%)	11.8%
Total Solids (TS) (%)	12.4%
VS/TS	95.5
Total Organic Carbon (g C/ L)	22.1
Total Nitrogen (g N/ L)	1.3
Total Phosphorus (g P/ L)	0.24
C:N	19.8

Source: Argonne National Laboratory staff calculations

An example of the two different walnut biochars used in the experiments and the particle size distribution can be seen in Figure 5. The smaller particle size increases the surface area of the fine walnut biochar. The fine walnut biochar has approximately 77 wt percent below a particle size 500 µm, whereas the coarse walnut biochar has only 24 wt percent below a particle size of 500 µm. The biochars were analyzed for proximate, ultimate and ash elemental analyses as seen in Table 14. The increased wt percent of ash and volatile matter of the fine walnut biochar determined by the proximate analysis shows that there is better degradability of the fine walnut biochar leading to a greater release of the divalent cations when compared to the coarse walnut biochar.

Furthermore, the fine walnut biochar has a higher concentration of magnesium and calcium than the coarse walnut biochar but the coarse biochar has greater amounts of potassium. Based on the ash percent, and calcium, magnesium and potassium concentration of the ash the fine walnut requires roughly 1.5 times as much biochar as the coarse walnut biochar to sequester the same amount of CO_2; however, this does not take into account particle size.

Figure 5: Example of Fine and Coarse Walnut Biochar and Particle Size Distribution

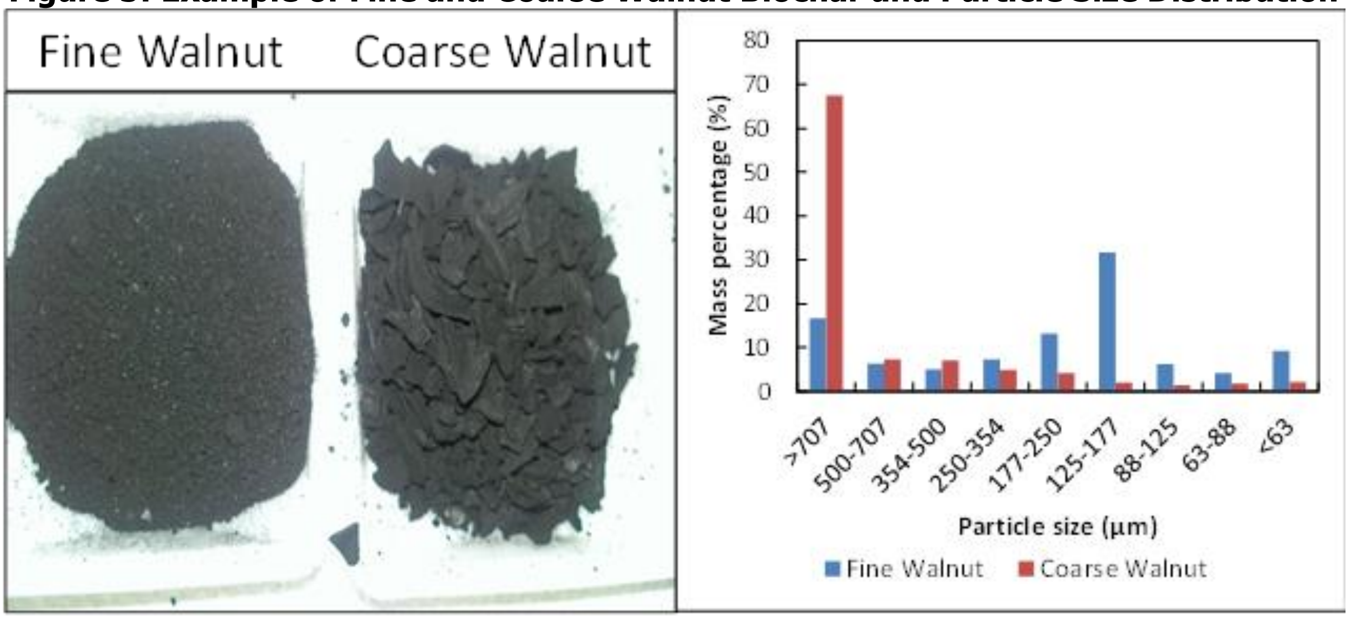


Photo Credit: Argonne National Laboratory

Table 14: Chemical Properties of Walnut Biochar

		Fine Walnut	Coarse Walnut
Proximate Analysis (wt %)	**Moisture**	2.7 ± 0.08	2.0 ± 0.10
-	**Ash**	43.2 ± 0.20	36.3 ± 0.13
-	**Volatile Matter**	21.2 ± 0.34	12.9 ± 1.09
-	**Fixed Carbon**	32.8 ± 0.41	48.8 ± 1.06
Ultimate Analysis (wt %)	**Moisture**	2.7 ± 0.08	2.0 ± 0.10
-	**Ash**	43.2 ± 0.20	36.3 ± 0.13
-	**S**	1.5 ± 0.03	0.0 ± 0.02
-	**C**	47.0 ± 0.25	61.0 ± 0.40
-	**H**	0.8 ± 0.04	0.5 ± 0.11
-	**N**	0.8 ± 0.07	0.6 ± 0.04
-	**O**	3.9 ± 0.56	0.0 ± 0.03
Elemental Analysis of Ash (wt % of ash)	**SiO2**	1.7 ± 0.08	1.4 ± 0.56
-	**Al2O3**	0.7 ± 0.20	1.1 ± 0.29
-	**TiO2**	0.0 ± 0.00	0.1 ± 0.02
-	**Fe2O3**	0.4 ± 0.01	0.3 ± 0.01
-	**CaO**	31.0 ± 0.72	19.2 ± 0.69
-	**MgO**	8.4 ± 0.13	5.6 ± 0.03
-	**Na2O**	23.4 ± 0.38	0.3 ± 0.01
-	**K2O**	0.2 ± 0.01	40.3 ± 1.45
-	**P2O5**	6.0 ± 0.03	6.2 ± 0.00
	SO3	8.0 ± 0.30	0.1 ± 0.02
	Cl	3.2 ± 0.03	1.9 ± 0.06
	CO2	14.8 ± 0.47	25.2 ± 0.26

Note: Data are shown in average values based on triplicate measurements ± standard deviations.

Source: Hazen Research, Inc.

Experimental Set-up

Batch digesters were used for the initial screening of the two walnut biochars' ability to sequester CO_2 from the biogas. The AD experiments were conducted in 650-mL Wheaton serum bottles at thermophilic temperature (55 °C ± 1 °C) with a working volume of 550 mL. The first screening experiment was run with a single replicate and tested the fine walnut (FW) biochar at three different dosages; 1.1, 2.1 and 4.2 g biochar/ g VS_{added} (5, 10, and 20 g of biochar per digester), against a positive control (PC) digester without the biochar. The second screening experiment was run in triplicate and tested the fine walnut and coarse walnut (CW) biochar each at a dosage of 1.8 g biochar/ g VS_{added} (10g biochar per digester). From here on out, the digesters will be designated by the type and amount of biochar added. For example a digester with 5g fine walnut biochar will be designated at FW5. The digesters were flushed with helium to maintain anaerobic conditions. Each digester was either placed in an MPA-200 Biomethane Potential Analyzer system (Challenge Technology, Springdale, AR) or in a New Brunswick's model I24 benchtop incubating shaker (Eppendorf, Hauppauge, NY). The MPA-200 system consists of an eight-channel respirometry-based unit for gas measurement, and a computer with pre-installed software for automated data recording. Each digester in the incubating shaker was attached to a multi-layer foil gas sampling bag (Restek, Bellefonte, PA) for gas collection and the volume of biogas produced was measured using a 100-mL high-performance gastight syringe (Hamilton, Reno, NV) manually on daily basis.

Two sized digesters were used in the two-stage semi-continuous experiments (Figure 6). The experiments were conducted at thermophilic temperatures (55 °C ± 1 °C). The operating conditions can be seen in Table 15. The PC digesters were operated in order to compare the gas production and methane content of digester with walnut to those without. The initial substrate to inoculum ratio was 1:1.3 for 1st stage digesters and 1:0.6 for 2nd stage digesters. For the 2nd stage digesters supplemented with walnut biochar, six times the daily addition listed in Table 15 was added at the beginning of the experiment. The digesters were flushed with helium to maintain anaerobic conditions. The digesters were allowed to operate in batch mode for three days for the bench scale digesters and seven days for the pilot scale digesters before semi-continuous operations were started. For the bench scale digesters (Figure 6A), the OLR was kept at 1.5 g VS/ L day for the length of the experiment. The bench scale digestion experiments used the Sixfors digester system. For the pilot scale digesters (Figure 6B), there was an upset at the Woodridge Wastewater Facility leading to very low total solids in the inoculum for the 1st stage digester resulting in lower than expected yields in the first two weeks of the experiment. The pilot scale experiments used the Bioflo digester system. The PC was run after the walnut supplemented digester experiment without removal of the digester contents in order to achieve faster acclimation of the microbes to the operating conditions. During both trials, the initial OLR was 1 g VS/ L day and was gradually increased to 2 g VS/ L day over the course of the experiment. The digesters were fed 1-2 times a day. Table 15 lists the average pH in each of the digesters after the 3-6 days of acclimation period.

Figure 6: Digester Systems Used for Semi-Continuous Experiments

See Table 15 for Operating Conditions.

Photo Credit: Argonne National Laboratory

Table 15: Operating Conditions for Two Digester Systems

Bench Scale or Pilot Scale	Bench	Bench	Bench	Bench	Pilot	Pilot	Pilot	Pilot
Parameter	Positive Control	Positive Control	Walnut	Walnut	Positive Control	Positive Control	Walnut	Walnut
Stage	Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2
Working Volume (L)	0.4	0.4	0.4	0.4	9.6	9.6	9.6	9.6
HRT (days)	15	30	15	30	15	30	15	30
Biochar (g/day)	0	0	0	0.25	0	0	0	6.00
pH*	4.8	7.2	4.8	7.7	4.5	7.4	4.9	7.7
pH range*	4.5-5.6	6.9-7.6	4.5-5.5	7.4-7.8	4.2-4. 8	7.2-7.7	4.6-5.5	7.6-8.0

*Reported pH and pH range is based after the 3-7 day acclimation period

Source: Argonne National Laboratory staff calculations

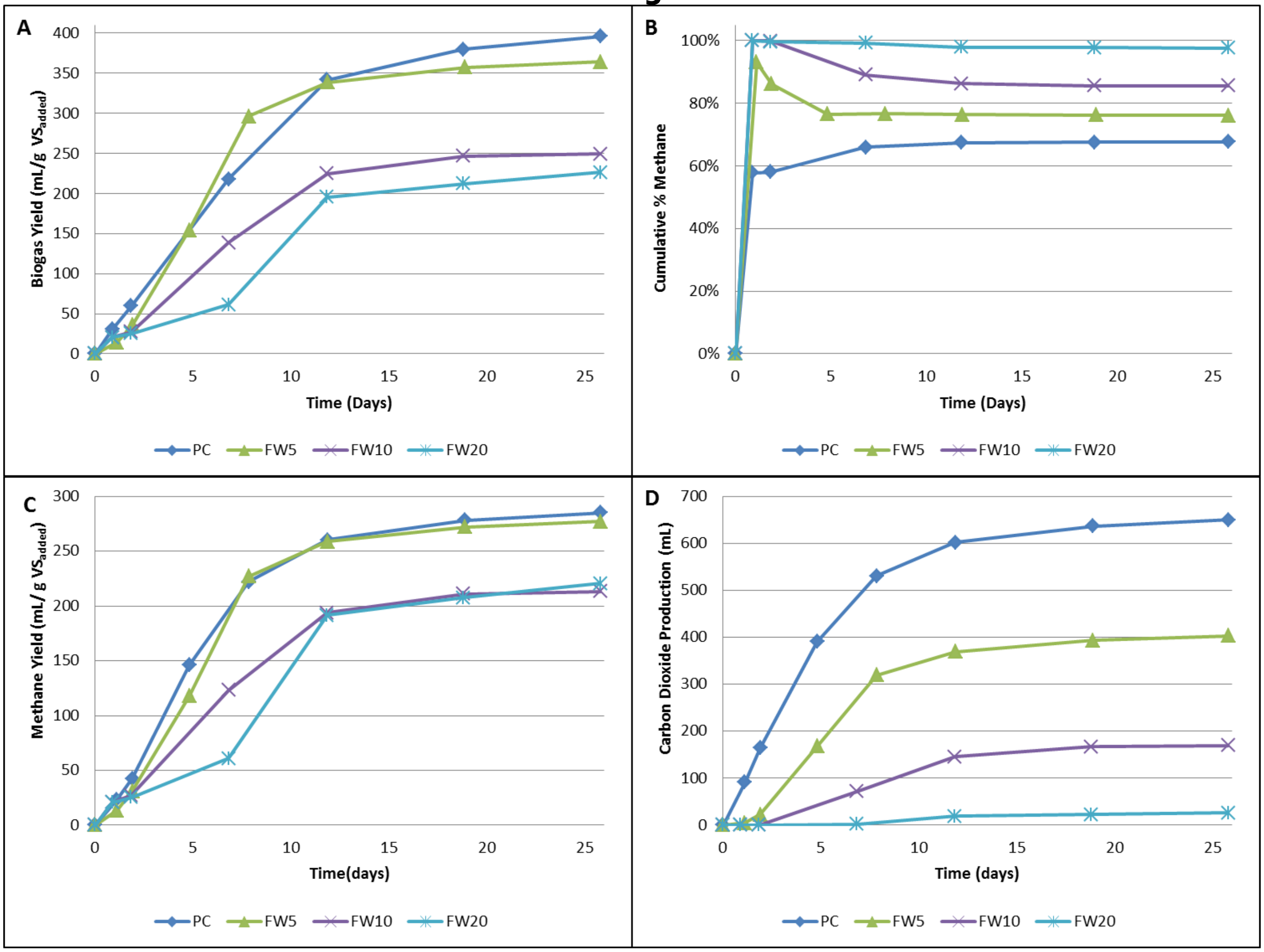
Gas volume measurements and gas samples from the headspace were taken up to once per day based on gas production rates. Gas volume measurements were conducted using multi-layer gas sampling bags for the bench scale digesters and a wet tipping system for the pilot scale digesters. Gas samples were analyzed for methane and CO_2 content. Gas samples were normalized to assume 100 percent biogas (methane and CO_2 only) was produced. Typical biogas measurements were 90-95 percent of the total gas in the 2nd stage digesters and approximately 50 percent of the total gas in the 1st stage digesters. Liquid samples were taken periodically to measure chemical oxygen demand (COD), total organic carbon (TOC), total alkalinity, total phosphorous, total nitrogen and ammonia- nitrogen by using methods provided by HACH Company (Loveland, CO). Samples were taken for total metal concentrations before and after the experiment for the bench scale digesters and approximately once a week for the pilot scale digesters. Total metal concentrations were analyzed by Inductively Coupled Plasma using U.S. EPA Methods 200.7/200.8.

Results

Batch Experiments

The batch screening experiments were terminated when the daily biogas production reached less than 1 percent of the total biogas production. For the first screening of the fine walnut biochar, the digesters were run with a single replicate for 26 days. Figure 7 shows the biogas yield (mL/ g VS_{added}), methane content (percent v/v), methane yield (mL/ g VS_{added}), and CO_2 production (mL) for the digesters for the fine walnut biochar experiment. The PC has a statistically higher biogas yield (p-value <0.002 for all results) compared to the FW5, FW10 and FW20 digesters (Figure 7A). The methane content was initially above 93 percent for the FW5 digester and at 100 percent for the FW10 and FW20 digester whereas the PC had an initial methane content of 58 percent (Figure 7B). The methane content stabilized after day 7. The PC digester averaged 67.6 percent for the remainder of the experiment. However, the methane content is statistically higher in the walnut supplemented digesters compared to the PC with the FW5 digester having an average 76.4 percent methane (p-value <0.0001), the FW10 digester having 86.6 percent methane (p-value <0.0001) and the FW20 digester having 98.1 percent methane (p-value <0.0001). There is no inhibition in the FW5 digester based on the methane yield comparison to the PC digester (p-value 0.0698) and there is no statistical difference in the methane yield between the FW10 and FW20 digesters (p-value 0.3569); however, there is a 23 percent reduction in methane yield between the PC and FW10/FW20 digesters (Figure 7C). Most remarkably, the CO_2 volume (mL) is reduced by 1.6 times in the FW5 digester compared to the PC without any loss in methane production. Furthermore, the FW10 digester had a 3.8 times reduction and the FW20 digester had a 23.9 times reduction in CO_2 compared to the PC (Figure 7D) which may be due in part to the lower biogas production. Based on these results the 10 g fine walnut loading was selected for further screening. Also, the volatile solid loading in the digesters was increased by approximately 15 percent in order to decrease the inhibition by the fine walnut biochar.

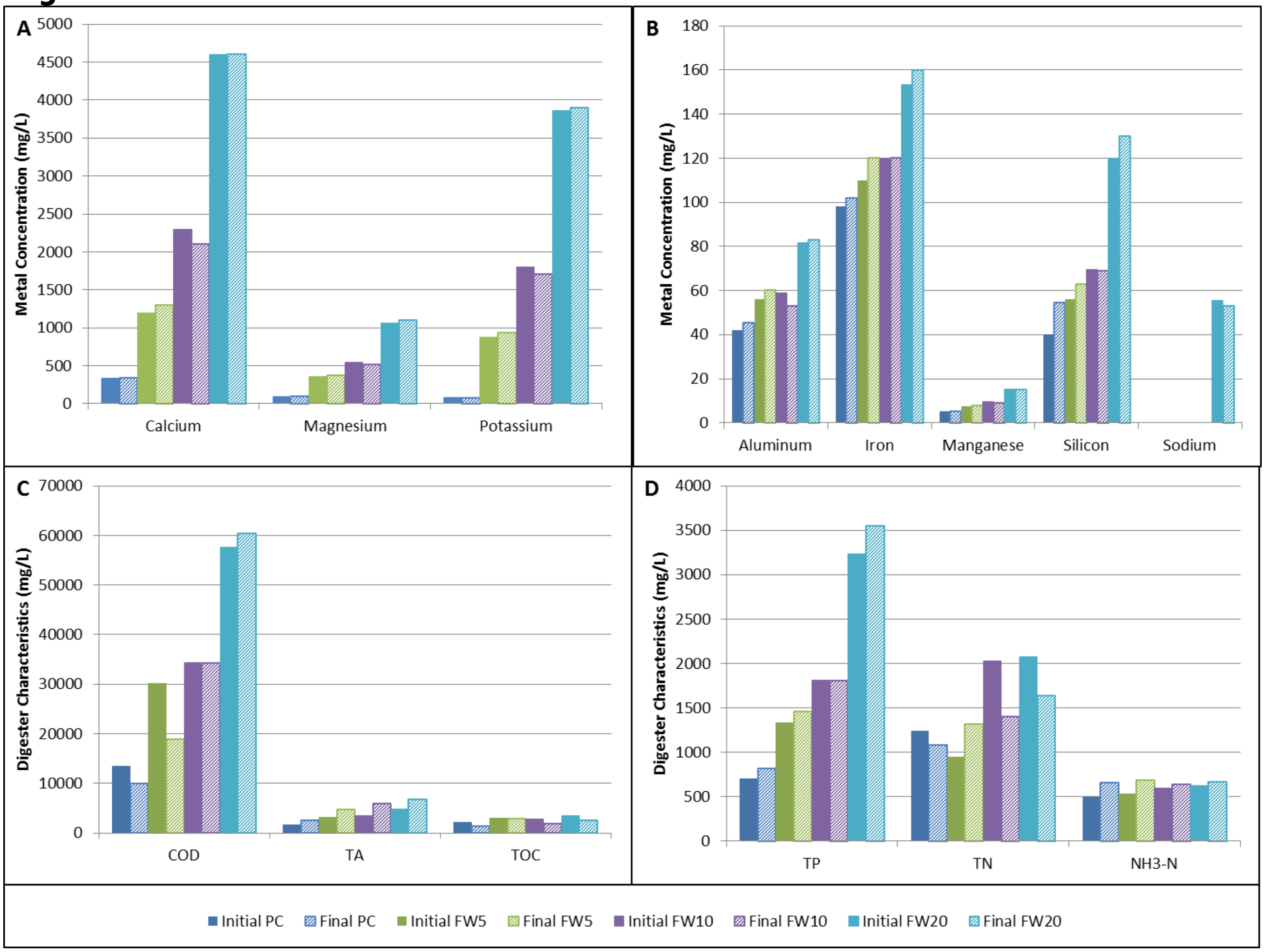
Figure 7: Results of Batch Anaerobic Digesters With Different Fine Walnut Biochar Dosages



Source: Argonne National Laboratory staff calculations

The metal concentration and sludge characteristics before and after AD can be seen in Figure 8. In general, the metal concentration increased with increasing biochar addition (Figure 8A and 8B). The highest metal concentrations were for calcium, magnesium and potassium (Figure 8A). Similar to the metal concentration, the COD, total alkalinity (Figure 8C) and total phosphorous (Figure 8D) increased with increasing biochar addition. The COD did not decrease in the higher concentrations of biochar addition either due to inhibition, the single replicate or the decrease not being discernable from the release of carbon in the biochar. However, the TOC decreased by similar in all digesters except for the FW5, which had a smaller change in concentration. Furthermore, the total alkalinity and total phosphorous increased during the AD.

Figure 8: Metal Concentration Before and After Batch AD with Fine Walnut Biochar



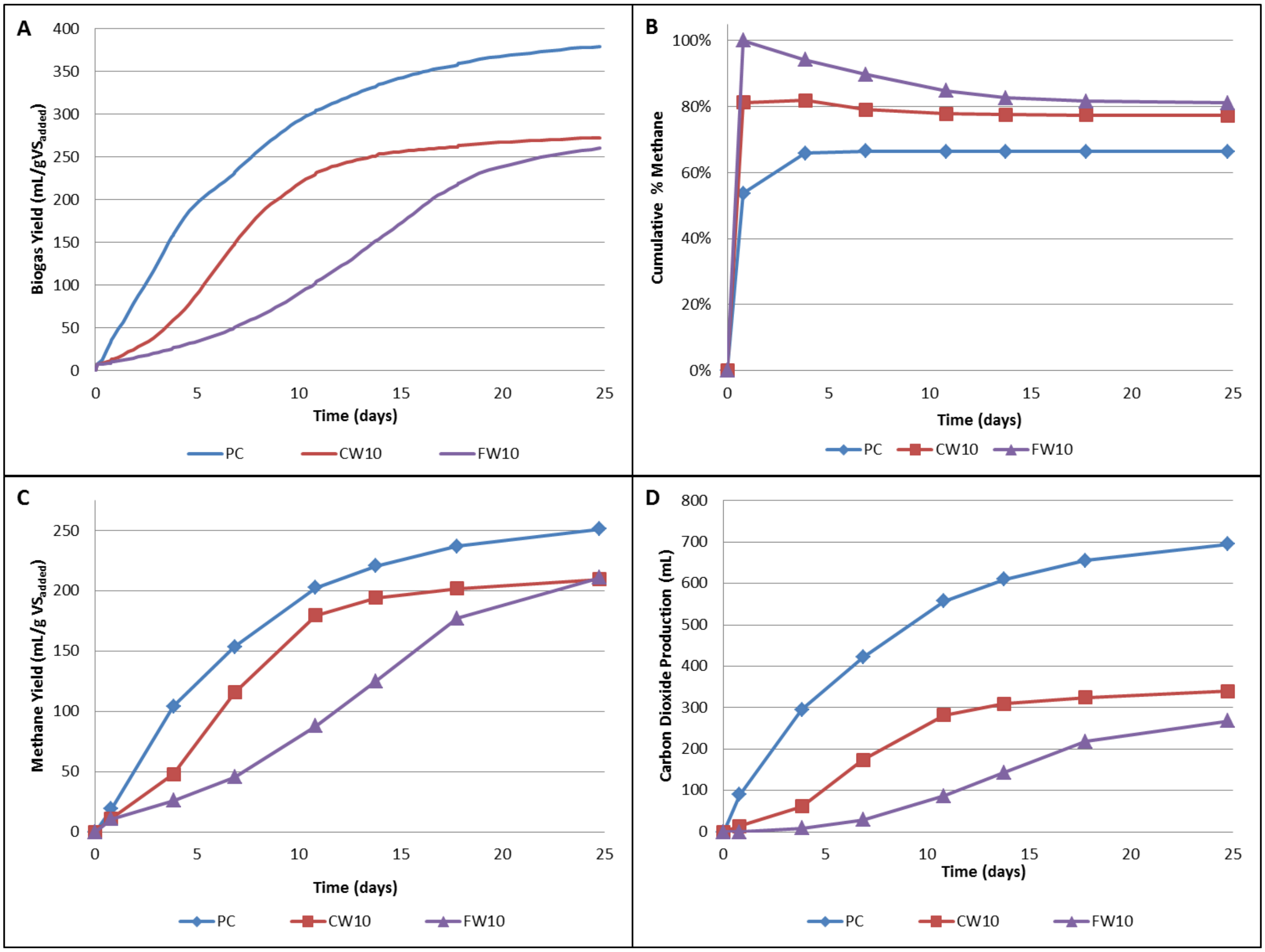
COD: chemical oxygen demand (mg COD/L), TA: total alkalinity (mg CaCO3/L), TOC: total organic carbon (mg C/L), TP: total phosphorous (mg P/L), TN: total nitrogen (mg N/L), and NH3-N: ammonia nitrogen (mg NH3/L).

Source: Argonne National Laboratory staff calculations

For the second experiment with the fine and coarse walnut biochar, the test digesters were run in triplicate and the PC in duplicate for 25 days. Figure 9 shows the biogas yield (mL/ g VS_{added}), normalized percent methane (percent), methane yield (mL/ g VS_{added}), and CO_2 production (mL) for the digesters for the fine and coarse walnut biochar screening. The PC digesters has a statistically higher biogas yield (p-value <0.0001) than the CW10 digesters, and the CW10 digesters had a statistically higher biogas yield (p-value <0.0001) than the FW10 digesters (Figure 9A). Again, the initial methane content for the FW10 digester was at 100 percent whereas the CW10 digester had an initial 81.3 percent methane content and the PC had an initial methane content of 54 percent (Figure 9B). The methane content stabilized in the PC after day 4 with an average of 66.3 percent for the remainder of the experiment. The methane content was statistically higher in the walnut supplemented digesters with the CW10 digester having an average 78.4 percent methane content and the FW10 digester having an average 85.7 percent methane content (p-value <0.0001 for both). The methane content of the FW10 digester is considered to be statistically higher than the CW10 digester (p-value

0.0093). The methane yields (Figure 9C) were all considered to be statistically different (p-value <0.034 for all conditions) showing slight inhibition from the biochar concentration in the digester. The CW10 digesters had a 2.1 times reduction in CO_2 production and the FW10 digesters has a 2.5 reduction in CO_2 production compared to the PC (Figure 9D).

Figure 9: Results of Batch Anaerobic Digesters with Coarse and Fine Walnut Biochar

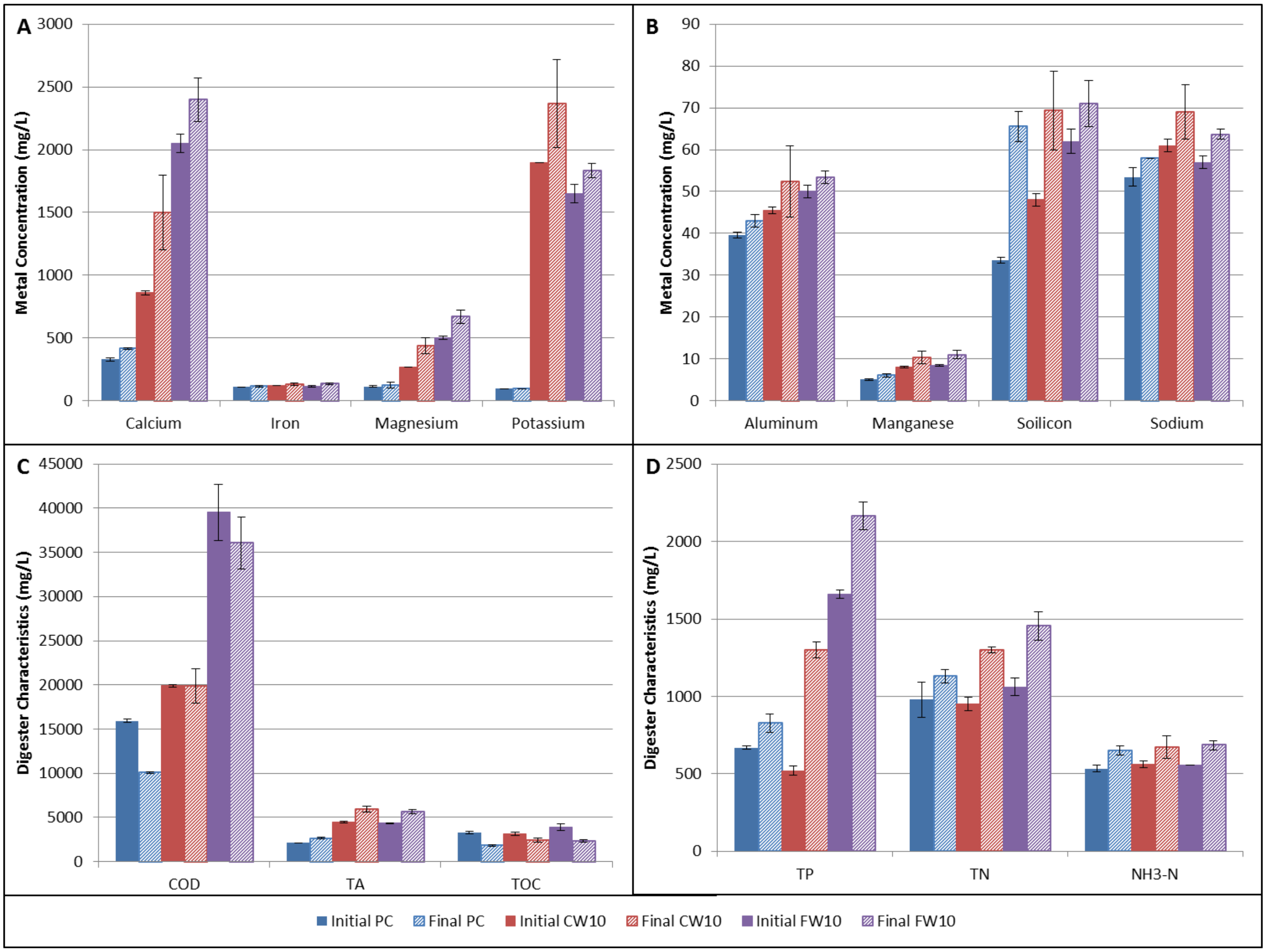


Source: Argonne National Laboratory staff calculations

As to be expected from the elemental analysis of the ash of the two different biochars (Table 15), the FW10 digester had more calcium and magnesium but less potassium released into the digesters than the CW10 digester (Figure 10A). Also, as expected, the two biochars released similar amounts of iron (Figure 10A), aluminum, manganese, silicon, and sodium (Figure 10B) into the digesters. The FW10 digester had a much higher COD (Figure 10C) than the PC and CW10 digesters possible due to the smaller particle size being easier to digest during the AD process. However, there is no significant difference in total alkalinity increase (p-value 0.2666) or TOC decrease (p-value 0.5023) between the PC, FW10 and CW10 digesters. Surprisingly, the total phosphate is much higher in the fine walnut biochar supplemented digester even though the amount of phosphorous is not very different in the biochar itself (Figure 10D).

This again may be due to the difference in particle size between the two biochars allowing for greater dissolution in the fine walnut biochar.

Figure 10: Metal Concentration Before and After Batch AD with Fine Walnut Biochar



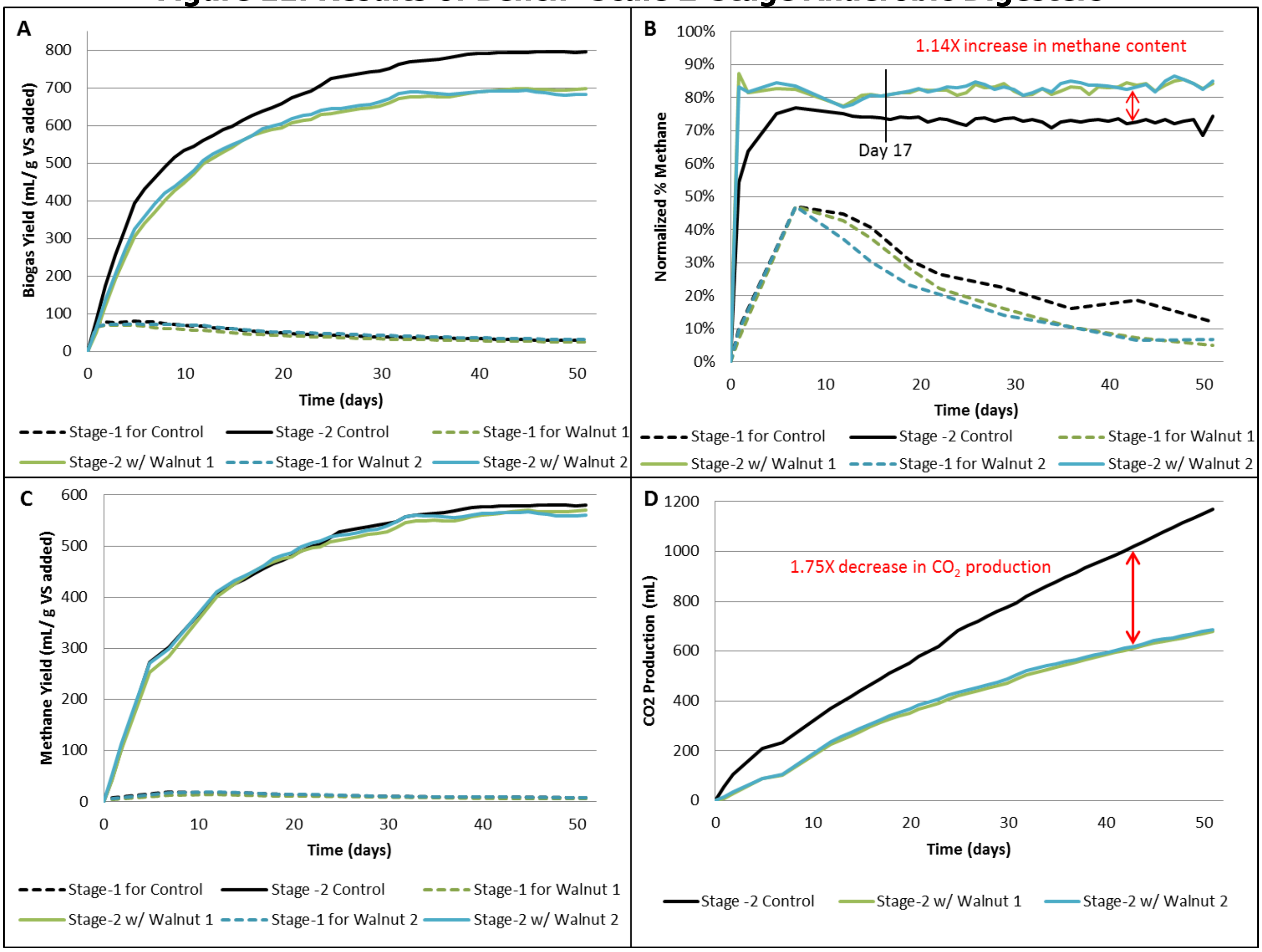
COD: chemical oxygen demand (mg COD/L), TA: total alkalinity (mg CaCO3/L), TOC: total organic carbon (mg C/L), TP: total phosphorous (mg P/L), TN: total nitrogen (mg N/L), and NH3-N: ammonia nitrogen (mg NH3/L).

Source: Argonne National Laboratory staff calculations

Bench Scale Semi-Continuous Experiments

For the bench scale digesters, the two-stage PC digester had a single replicate and the two-stage FW digesters where the walnut was supplemented to the 2nd stage was run in duplicate. The experiment lasted for 51 days. Figure 11 shows the biogas yield (mL/ g VS_{added}), normalized percent methane (percent v/v), methane yield (mL/ g VS_{added}), and CO_2 production (mL) for the 2nd stage over the study. Figure 11 shows that the 1st stage digesters have very similar results for all conditions. The two 2nd stage FW digesters also have very similar results. The 2nd stage FW digesters have a statistically lower biogas yield (p-value <0.0001) via students paired t-test compared to the 2nd stage PC digester (Figure 11A). However, the lower biogas yield is due to the CO_2 sequestration in the 2nd stage FW digesters. The 2nd stage FW digesters have statistically higher methane content (percent) compared to the 2nd stage PC digester (Figure 11B). After day 17, the 2nd stage FW digesters have an average 83.0 percent ± 1.3percent methane content compared to the 2nd stage PC digester's average 73.0 percent ± 1.1 percent methane content (p-value <0.0001), hence there is 1.14X increase in methane content. Furthermore, there is only 1.1 percent difference in methane yield between the 2nd stage PC digester and 2nd stage FW digesters (Figure 11C). More significantly, there is a 1.75 times reduction in CO_2 production in the 2nd stage FW digesters compared to the 2nd stage PC digester (p-value > 0.0001, Figure 11D).

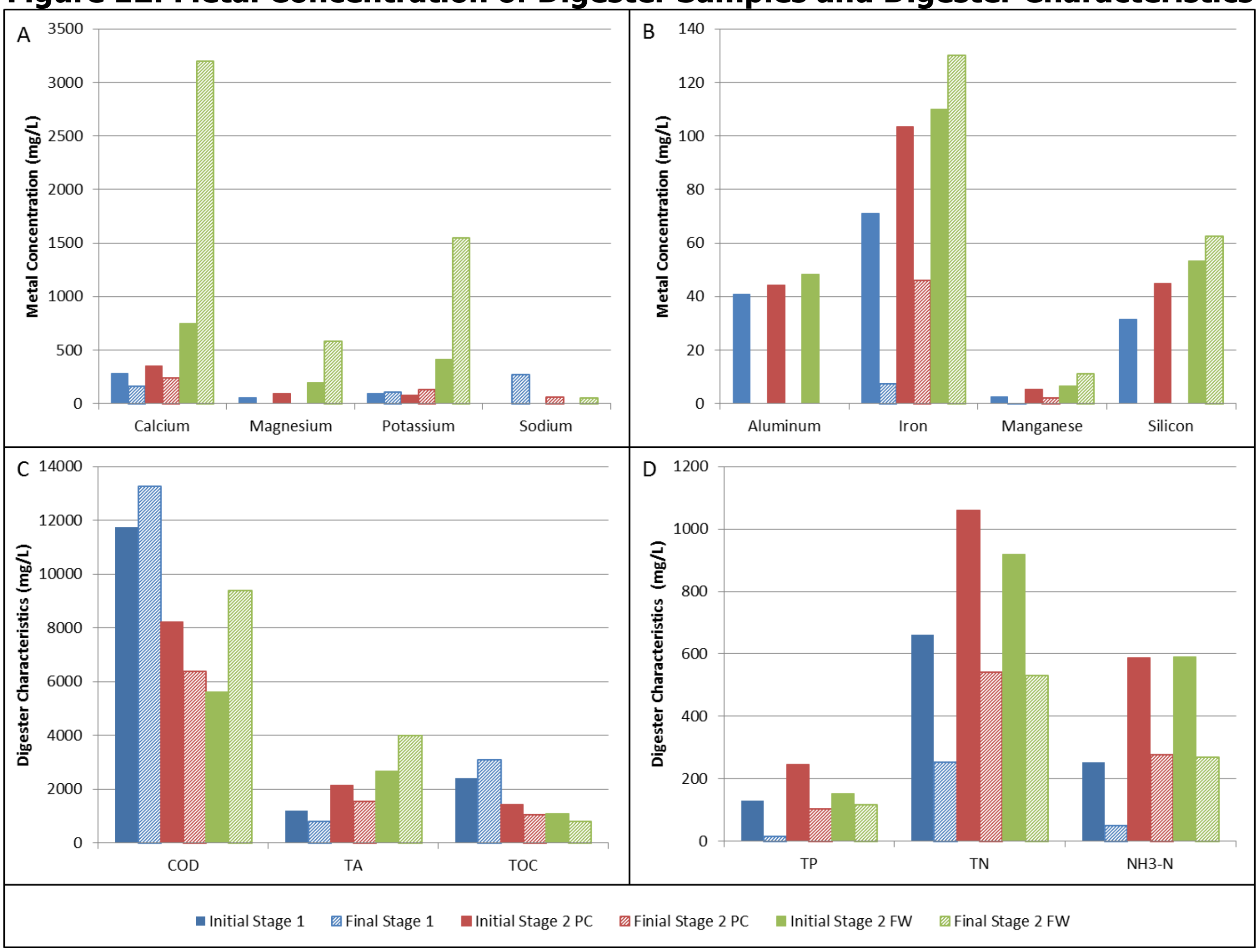
Figure 11: Results of Bench- Scale 2-Stage Anaerobic Digesters



Source: Argonne National Laboratory staff calculations

Figure 12 shows the metal concentration and digester characteristics before and after semi-continuous operation. The results from the before the experiment were run in triplicate and the results after the experiment were averaged for the same type of digester (i.e. the three 1st stage digester results were averaged). In the 1st stage digesters and 2nd stage PC digester, the metal concentrations decrease for all elements except for sodium and potassium which increased (Figure 12A and 12B). The increase in sodium for the 1st stage digesters may be due to pH adjustment with NaOH. The increase in potassium may have come from the food waste being fed to the digesters. However, in the 2nd stage FW digesters, the metal concentration increased for every metal except for aluminum. Calcium, magnesium and potassium had the largest increase in the 2nd stage FW digesters which is to be expected from the biochar analysis in Table 12. The change in digester characteristics were fairly linear during the experiment (data not shown). Figure 12C and 12D shows the concentration of various digester characteristics after the 4 day acclimation period and at the end of the experiment. In the 1st stage digester, the various digester characteristics all decreased during the course of the experiment, except for COD and TOC, which increased. The TOC/COD were low in the initial samples from the 1st stage digesters due to the 4 day accumulation period. After semi-continuous operation started, the TOC/COD values remained fairly constant. All of the parameters decreased in the 2nd stage digesters, except for the 2nd stage FW digester which has an increase in COD and total alkalinity. The increase in COD and total alkalinity is due to the increased concentration of the fine walnut biochar over the course of the experiment.

Figure 12: Metal Concentration of Digester Samples and Digester Characteristics



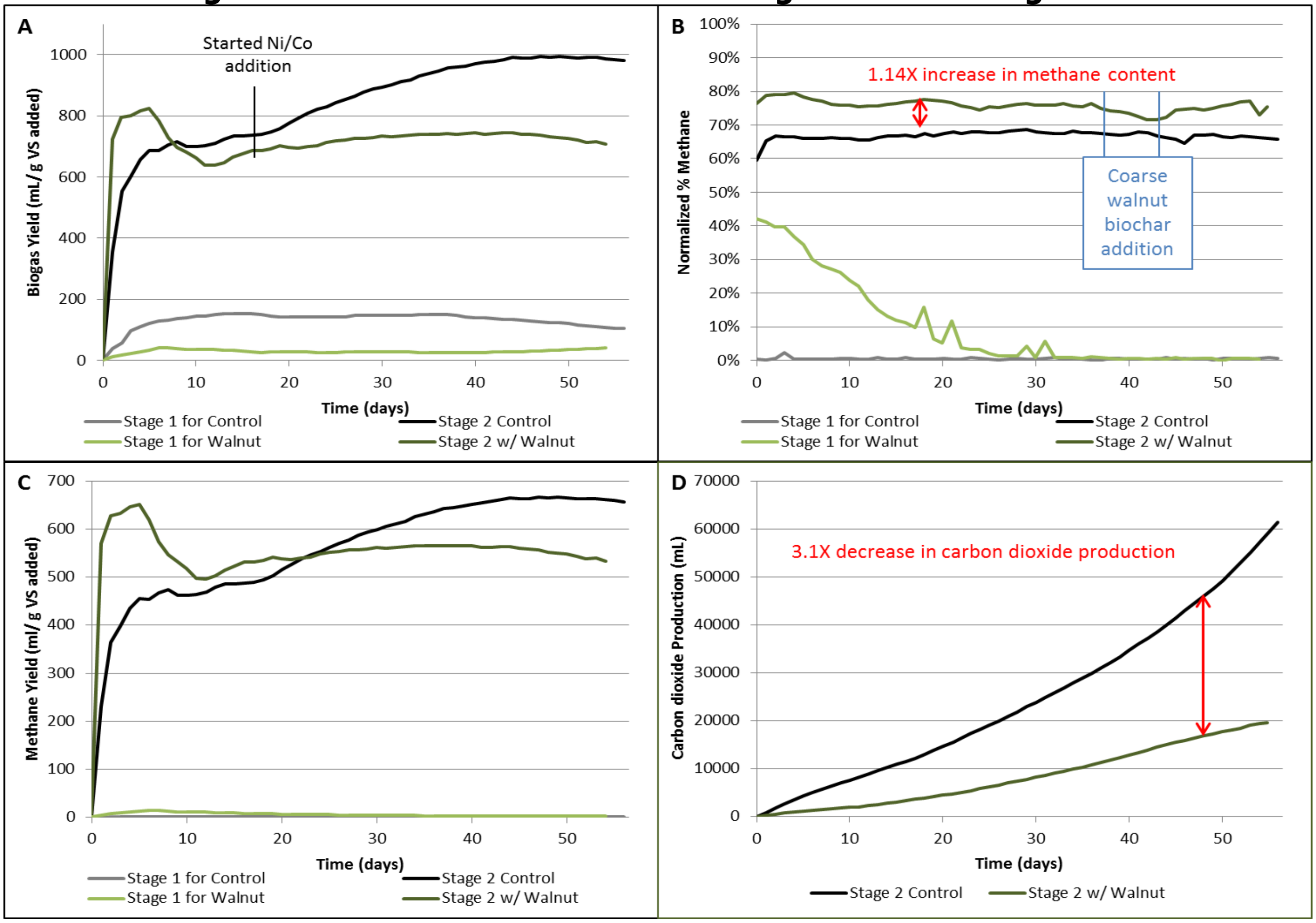
COD: chemical oxygen demand (mg COD/L), TA: total alkalinity (mg CaCO3/L), TOC: total organic carbon (mg C/L), TP: total phosphorous (mg P/L), TN: total nitrogen (mg N/L), and NH3-N: ammonia nitrogen (mg NH3/L).

Source: Argonne National Laboratory staff calculations

Pilot Scale Semi-Continuous Experiments

For the pilot scale digesters, after the 7 days acclimation period, the two-stage walnut supplemented digester ran for 55 days and the two-stage PC digester ran for 56 days. Figure 13 shows the biogas yield (mL/ g VS_{added}), normalized percent methane (percent v/v), methane yield (mL/ g VS_{added}), and cumulative CO_2 production (mL) for the 2nd stage after the 7 day acclimation period. The 1st stage digester for the control experiment has a much higher biogas yield (Figure 13A) and lower methane content (Figure 13B) than the 1st stage digester for the walnut supplemented experiment. The 2nd stage control digester had a statistically higher biogas yields compared to the 2nd stage walnut supplemented digester (p-value <0.0001, Figure 13A). The methane content of the 2nd stage walnut supplemented digester fluctuates with the various walnut loading rates and types of walnut biochar used. The best results were obtained with a loading rate of 6 g biochar/ 10 liter on days 0 to 6 with an average methane content of 78.5 percent. For the first 35 days, the 2nd stage walnut supplemented digesters was amended with fine walnut biochar and had an average 76.5percent $\pm$ 1.2 percent methane content. The 2nd stage digester was amended with coarse walnut biochar from day 36 to 44 which reached a low of 71.5 percent methane. The biochar amendment was switched back to fine walnut biochar and after a 4 day recovery period, the methane content averaged 75.6 percent for the remainder of the experiment. However, there is a similar difference overall in methane content between the 2nd stage digesters in the bench and pilot scale experiments. Even with the fluctuations in methane content, the 2nd stage walnut supplemented digester has a statistically higher methane content compared to the 2nd stage control digester's average 66.8 percent $\pm$ 1.3 percent methane content (p-value <0.0001) which is a 1.14x increase in methane content (Figure 13B). Furthermore, the 2nd stage walnut supplemented digester does not have a statistical different methane yield than the 2nd stage control digester (p-value 0.6836, Figure 13C). More significantly, there is a 3.1 times reduction in CO_2 production in the 2nd stage walnut supplemented digesters compared to the 2nd stage control digester (p-value > 0.0001, Figure 13D).

Figure 13: Results of Pilot-Scale 2-stage Anaerobic Digesters



Source: Argonne National Laboratory staff calculations

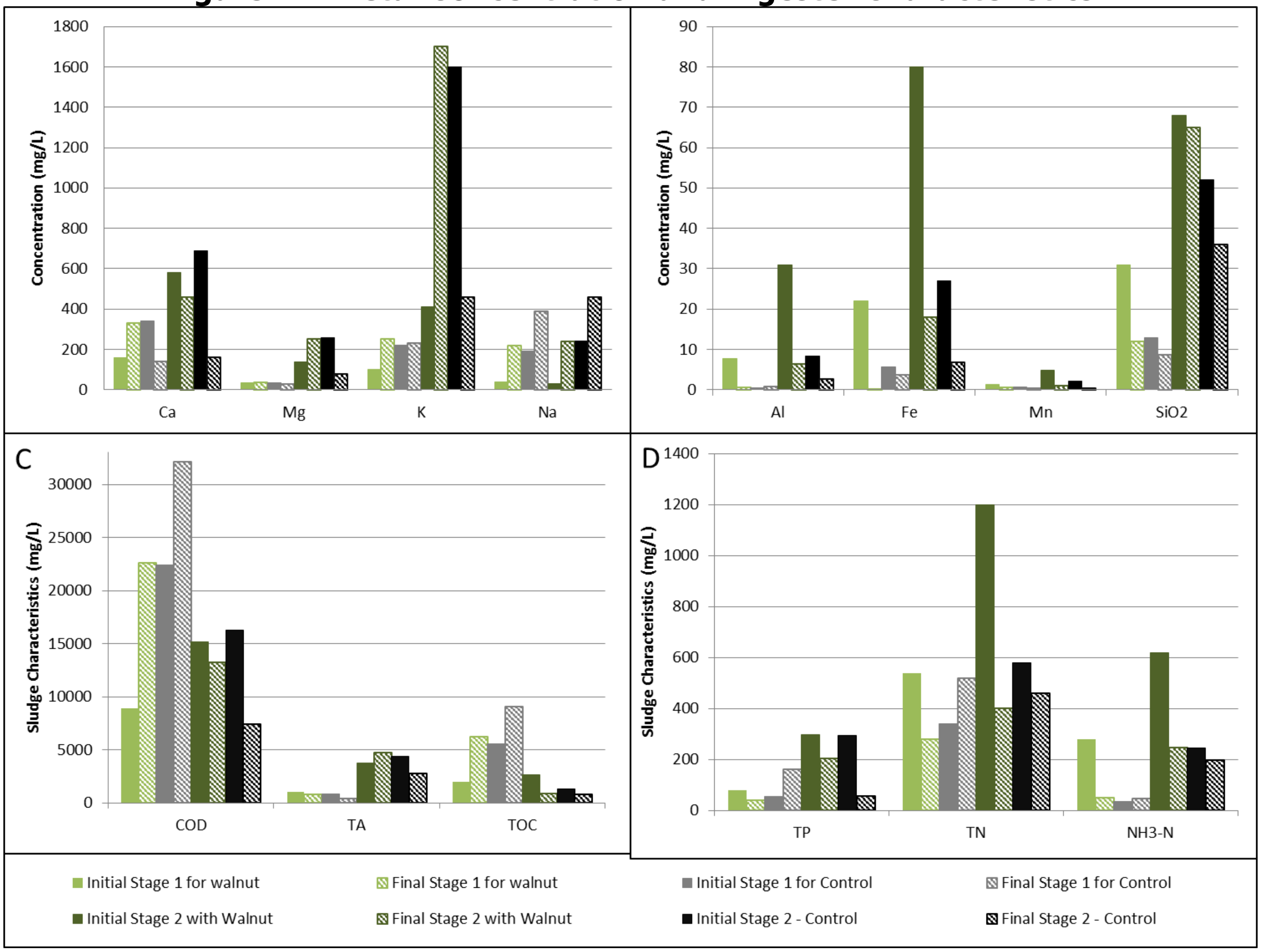
Figure 14 shows the metal concentration and digester characteristics before and after semi-continuous operation for the walnut supplemented digester. Samples were taken once a week for the metal concentration analysis and taken every day or every other day for digester characteristics. The analyses were only conducted once for each data point; however, the results showed a fairly linear trend over the course of the experiment (data not shown).

For the 2-stage walnut supplemented experiment, the metals with a higher concentration (Ca, Mg, K and Na) increased in both the 1st stage digester and the 2nd stage walnut supplemented digester (Figure 14A) except for Mg in the 1st stage which stayed the same and Ca in the 2nd stage which decreased. The increase in sodium may be due to pH adjustment in the 1st stage digester using NaOH. The metals with a lower concentration (Al, Fe, Mn and SiO_2) all decreased in both digesters (Figure 14B). The linear change in metal concentration over the course of the experiment indicates that the metals were from the sludge used to inoculate the digesters and not the food waste used as the feedstock. The digestate from biochar supplemented digesters has higher Ca, Mg, K and Fe content than the digestate from control digesters. The total Ca, Mg, K and Fe in the biochar-amended digesters increased by 290 percent, 330 percent, 370 percent and 270 percent, respectively. These results show that addition of biochar results in digestate with high fertilizer value. The low total solids in the inoculum for the 1st stage digester for the walnut supplement experiment was due to an upset at the Woodridge Wastewater Facility and can be seen in the low COD and TOC of the initial samples (Figure 14C). The final sample COD and TOC appear to be higher in the 2nd stage digester amended with biochar compared to the 2nd stage control digester due to the biochar addition. It should be noted that biochar stores the organic carbon in a recalcitrant form[22] which is resistant to microbial degradation. Hence, the biochar addition does not increase any bioavailable organic matter concentration in the digester. However, due to the harsh acidic conditions used to determine COD and TOC, the biochar did effect the results of these tests. Comparatively, in this study the digesters were operated at 55 °C with pH slightly basic range. The total alkalinity is higher in the 2nd stage digesters compared to the 1st stage due, in part, to walnut biochar addition. As the walnut biochar is being removed from the 2nd stage control digester, the alkalinity is decreased until day 32 where it remained a constant value (data not shown). Likewise, the total phosphate increased in the 2nd stage digester due to the walnut biochar addition. In the 2nd stage control digester, the total phosphate concentration reached a constant value after 42 days (Figure 14D).

---

22 Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S. 2010. Sustainable biochar to mitigate global climate change. *Nat Commun.*,1, 56, 1-9.

Figure 14: Metal Concentration and Digester Characteristics



COD: chemical oxygen demand (mg COD/L), TA: total alkalinity (mg CaCO3/L), TOC: total organic carbon (mg C/L), TP: total phosphorous (mg P/L), TN: total nitrogen (mg N/L), and NH3-N: ammonia nitrogen (mg NH3/L).

Source: Argonne National Laboratory staff calculations

Microbial Community Structure

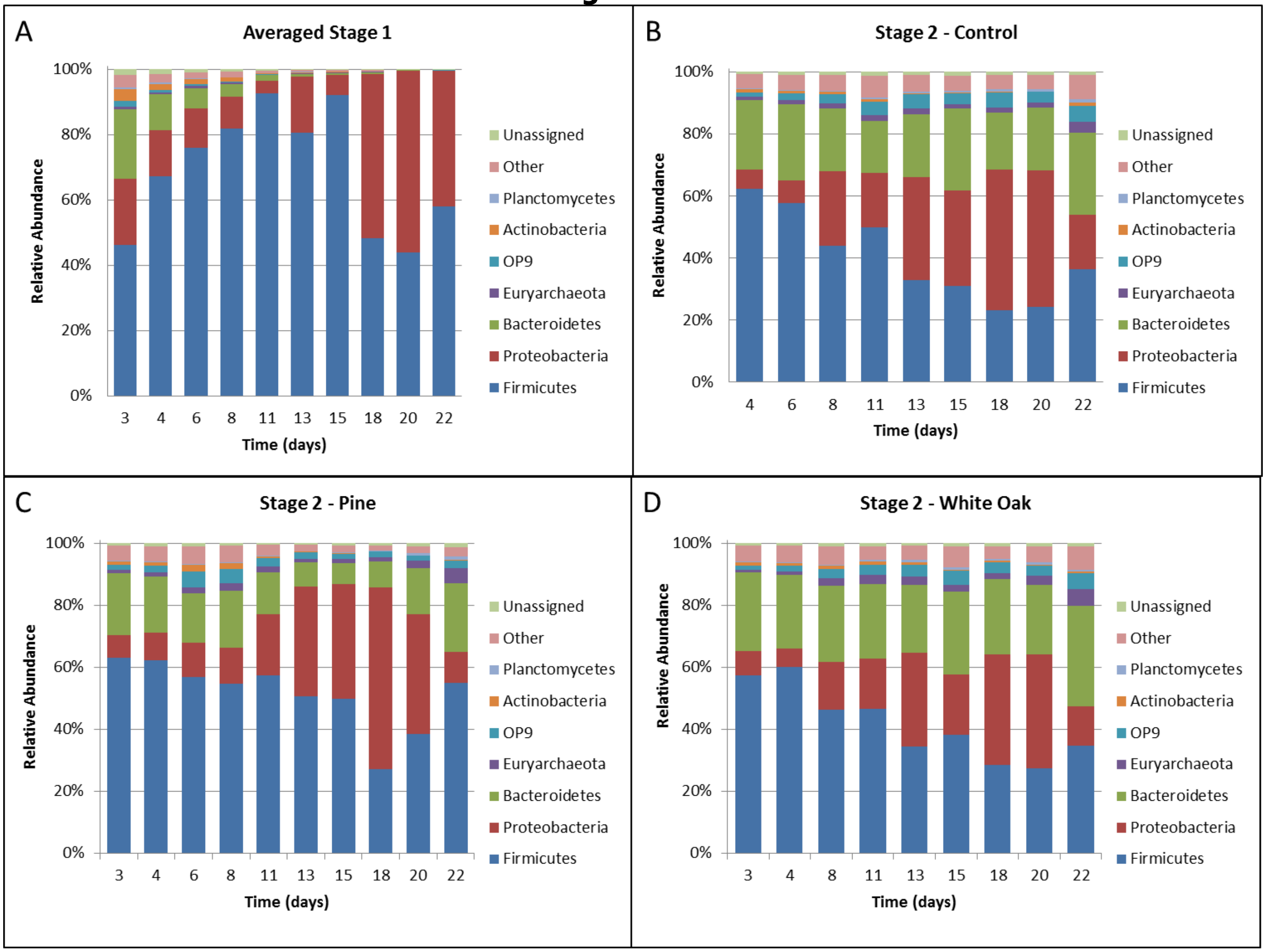
The microbial community structure was analyzed on a short semi-continuous experiment utilizing pine and white oak biochar that was available in the lab prior to receiving the walnut biochar (Figure 15). The results were very similar in the 1st stage digesters, an average of the three 1st stage digesters can be seen in Figure 15A. The dominant phyla were Firmicutes and Proteobacteria which had a combined relative abundance of greater than 90 percent after day 8 and greater than 99 percent in the later time points for the experiment. Clostridia were the largest class among the Firmicutes. Alphaproteobacteria was the largest class of Proteobacteria occupying up to 99 percent of the relative abundance in later time points. Proteobacteria and Firmicutes are important microbes in anaerobic digesters because the phyla contains the volatile fatty acid utilizing communities such a propionate, butyrate and acetate.[23]

For the 2nd stage digesters, the dominate phylums were still the Firmicutes and Proteobacteria; however, there combined relative abundance was only 60-70 percent in the 2nd stage control digester (Figure 15B) and 2nd Stage white oak supplemented digester (Figure 15D). The combined relative abundance of the Firmicutes and Proteobacteria reached approximately 85 percent in the 2nd stage pine supplemented digester possibly due to an error in pH adjustment (data not shown). Bacteroides had a larger role in the 2nd stage digesters with a relative abundance of 15-25 percent which is followed by the Euryarchaeia. The 2nd stage PC digester had 3.5 percent relative abundance on Euryarchaeia whereas the 2nd stage pine supplemented digester had 4.8 percent and the 2nd stage white oak supplemented digester had 5.2 percent on day 22. Among the Euryarchaeia, the dominant species was Methanothermobacter which is to be expected since the digesters were operated at thermophilic temperature (55 ^oC). The 2nd stage PC again had the lowest abundance of Methanothermobacter (86 percent of all Euryarchaeia) compared to the 2nd stage pine supplemented digester at 92 percent relative abundance and the 2nd stage white oak supplemented digester at 94 percent relative abundance. This indicates that the biochar addition has a positive effect on methogenic activity in the digesters.

---

23 Yang, Y., Yu, K., Xia, Y., Lau, F.T.K., Tang, D.T.W., Fung, W.C., Fang, H.H.P., Zhang, T. 2014. Metagenomic analysis of sludge from full-scale anaerobic digesters operated in municipal wastewater treatment plants. *Applied Microbiology and Biotechnology*, **98**(12), 5709-5718.

Figure 15: Microbial Community Structure for 2-stage Food Waste Anaerobic Digesters



Source: Argonne National Laboratory staff calculations

Field Work Support

Clean World sent food waste samples to Argonne for comparison to the food waste being fed to the pilot scale digesters at Argonne's lab. The results from the analysis can be seen in Table 16 below. In general, Clean World's food waste is 1.3 to 2 times stronger than food waste used at Argonne. The exceptions are total nitrogen (4.5 times higher), total alkalinity (9.6 times higher) and ammonia nitrogen (117 times higher). The higher concentration of total alkalinity and ammonia nitrogen may affect the comparison of the pilot scale digesters to the field scale digesters. The increased ammonia and alkalinity in Clean World's food waste samples may be due to the consumption of organic nitrogen resulting in metabolism generated alkalinity.[24] It is also important to note that the total alkalinity of Clean World's food waste

24 RE, S. 1996. Anaerobic Biotechnology for Industrial Wastewater, Archae Press. Nashville, TN.

samples were in the reported desirable range (2,000-5,000 mg/L as $CaCO_3$) for digester operation[25] which minimizes the benefit of the biochar addition.

Table 16: Food Waste Comparison from Clean World and Argonne National Lab

	Clean World's food waste (Avg.)	**Clean World's food waste** (St dev)	**Argonne Lab's Food waste** (Avg.)	**Argonne Lab's Food waste** (St dev)	**Ratio CW:ANL**
TV (%)	4.94%	0.02%	3.14%	0.11%	1.6
VS (%)	3.91%	0.02%	2.97%	0.11%	1.3
pH	5.02	0.01	3.77	0.10	1.3
COD (mg COD/L)	69460	1565	43720	3370	1.6
Total Alkalinity (mg $CaCO_3$/L)	3305	66	343	6	9.6
Total Organic Carbon (mg C/L)	20290	1213	11213	1526	1.8
Total Phosphorous (mg P/L)	698	61	347	33	2.0
Total Nitrogen (mg N/L)	2535	100	560	17	4.5
Ammonia Nitrogen (mg NH_3/L)	1210	44	10	3	117.1

N= 4 for Clean World's food waste and n=3 for Argonne Lab's food waste

Source: Argonne National Laboratory staff calculations

Clean World also sent Argonne an additional cow manure biochar to compare to the fine and coarse walnut biochar. An example of the cow manure biochar and the particle size analysis can be seen in Figure 16. The cow manure biochar has approximately 56 wt percent below a particle size of 500 μm which is between the fine and coarse walnut biochar as discussed above. The cow manure biochars was also analyzed for proximate, ultimate and ash elemental analyses as seen in Table 17. The cow manure biochar has a higher wt percent of ash and volatile matter than both the fine and coarse walnut biochar (see Table 14 for chemical properties of the fine and coarse walnut biochar) indicating that the cow manure biochar may better degradability leading to a greater release of the divalent cations. However, the cow manure biochar has only 0.5 to 0.75 the wt percent of ash for calcium compared to the walnut biochars. The cow manure biochar also has a similar magnesium content (wt percent) compared to the fine walnut biochar but less potassium compared to the coarse walnut

25 Metcalf, Eddy. 2003. *Wastewater Engineering: Treatment and Reuse*. *4th ed*. McGraw-Hill, Boston.

biochar. Based on the ash percent, and calcium, magnesium and potassium concentration of the ash the cow manure biochar should be able to sequester the same amount of CO_2 as the fine walnut biochar. These results indicate that the cow manure biochar may be an acceptable replacement for the fine walnut biochar.

Figure 16: Example of Cow Manure Biochar and Particle Size Distribution

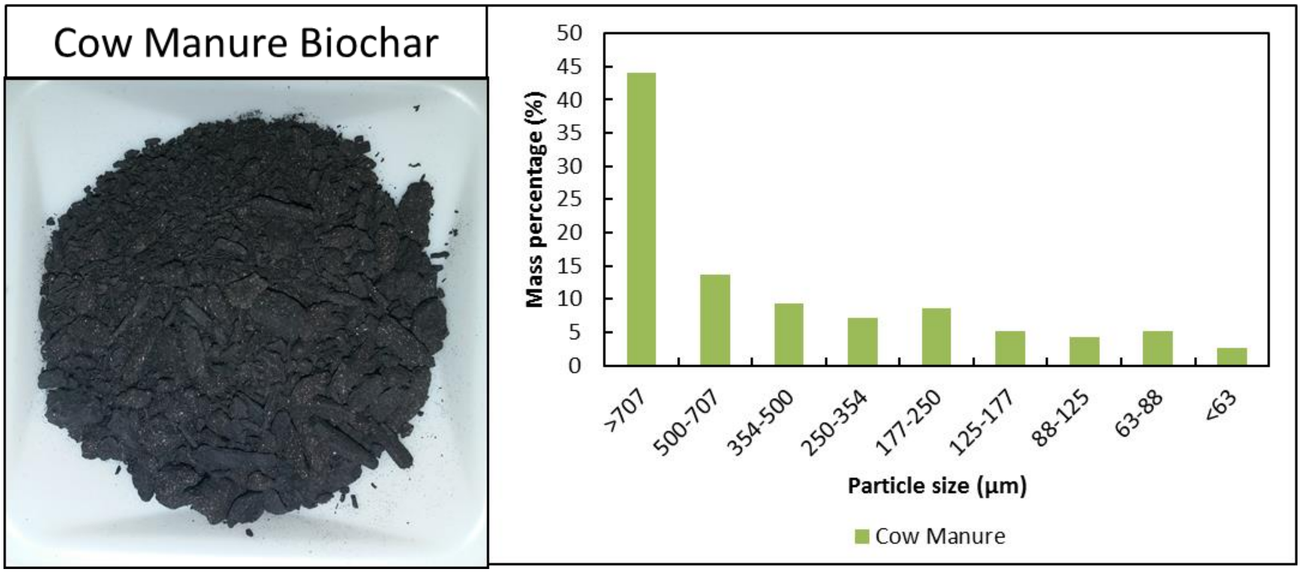


Photo Credit: Argonne National Laboratory

Table 17: Chemical Properties of Walnut Biochar

		Cow Manure
Proximate Analysis (wt %)	**Moisture**	4.7
-	**Ash**	49.1
-	**Volatile Matter**	22.6
-	**Fixed Carbon**	23.7
Ultimate Analysis (wt %)	**Moisture**	4.7
-	**Ash**	49.1
-	**S**	0.3
-	**C**	33.3
-	**H**	1.9
-	**N**	1.2
-	**O**	9.6
Elemental Analysis of Ash (wt % of ash)	**SiO2**	41.5
-	**Al2O3**	7.5
-	**TiO2**	0.4
-	**Fe2O3**	3.1
-	**CaO**	14.7
-	**MgO**	8.6
-	**Na2O**	1.7
-	**K2O**	9.7
-	**P2O5**	5.2
-	**SO3**	1.5
-	**Cl**	2.2
-	**CO2**	3.8

Source: Hazen Research, Inc.

Discussion: Bench Scale Digester Tests

Biochar Properties

The fine walnut biochar has a smaller particle size compared to the cow manure biochar and coarse walnut biochar. For the fine walnut biochar, 77 wt percent of the biochar has a particle size less than 500 μm compared to the 56 wt percent for the cow manure biochar and coarse walnut biochar having only 24 wt percent of the biochar with a particle size below 500 μm. The smaller particle size of the fine walnut biochar increased the porosity of the biochar and provides a large surface area for CO_2 adsorption. All of the biochar types have high ash content (49.1 wt percent for the cow manure, 43.2 wt percent for the fine walnut and 36.3 wt percent for the coarse walnut biochar), as compared to some other wood-derived biochar (ash content < 5 wt percent).[26] However, the cow manure and fine walnut biochar have relatively low carbon contents (33.3 percent and 47.0 percent, respectively) compared to the coarse walnut biochar (61.0 percent). Furthermore, the fine walnut biochar has higher concentrations of surface-rich active sites such as 31.0 percent CaO and 8.4 percent MgO compared to the coarse walnut biochar 19.2 percent CaO and 5.6 percent MgO and the cow manure 14.7 percent CaO and 8.6 percent MgO. The cow manure biochar looks promising based due to similar properties to the fine walnut biochar.

Anaerobic Digestion Experiments

The AD experiments testing the walnut biochar's ability to promote in-situ CO_2 sequestration were conducted at thermophilic temperature because thermophilic AD has many inherent advantages over mesophilic AD. Some of the advantages of thermophilic AD including faster reaction rate, higher biogas production, less foaming occurrence and enhanced pathogen reduction.[27, 28] The elevated temperature will also enhance the leaching and dissolution of the alkali and alkaline earth metals (Ca, Mg, and K) from the biochar.[29, 30] The digestibility of food waste is also improved by conducting AD under alkaline condition at thermophilic

---

26 Keiluweit, M., Nico, P.S., Johnson, M.G., Kleber, M. 2010. Dynamic molecular structure of plant biomass-derived black carbon (biochar). *Environ Sci Technol*, **44**(4), 1247-1253.

27 De la Rubia, M.A., Riau, V., Raposo, F., Borja, R. 2013. Thermophilic anaerobic digestion of sewage sludge: focus on the influence of the start-up. A review. *Crit Rev Biotechnol*, **33**(4), 448-60.

28 Suryawanshi, P.C., Chaudhari, A.B., Kothari, R.M. 2010. Thermophilic anaerobic digestion: the best option for waste treatment. *Crit Rev Biotechnol*, **30**(1), 31-40.

29 Pan, S.-Y., E., C.E., Chiang, P.-C. 2012. CO_2 capture by accelerated carbonation of alkaline wastes: A review on its principles and applications. *Aerosol and Air Quality Research*, **12**(5), 770-791.

30 Sanna, A., Uibu, M., Caramanna, G., Kuusik, R., Maroto-Valer, M.M. 2014. A review of mineral carbonation technologies to sequester CO_2. *Chem Soc Rev*, **43**(23), 8049-80.

temperature.[31] Additionally, the two-stage system may be less susceptible to system overloading, acidification and digester upset when compared to a single stage system even when fed only intermittently with high strength waste such as food waste.[32] Furthermore, ARP's digesters consist of the stage system and are also run at thermophilic temperature. It was very important to simulate the field conditions in the lab to provide guidance for the field work.

Methane Content and Carbon Dioxide Sequestration

The AD of the food waste was observed to benefit from the walnut biochar addition with regard to the CO_2 sequestration in the biogas for both the batch and semi-continuous experiments. The biochar particle size provides a large surface area for CO_2 adsorption, as discussed before. The high ash content and high concentration of alkali and alkaline earth metals (Ca, Mg, and K) in the biochar contributes to the accelerated carbonation reaction. In the batch experiments, the fine walnut biochar amended digesters had 76.3 percent to 98.1 percent methane content which equates to 1.6 to 23.9 times less CO_2 production, depending on the dose when compared to the PC (Figure 7B and 7D). The coarse walnut biochar amended digesters had a 78.5 percent methane content which equates to 2.0 times less CO_2 production compared to the PC (Figure 9B and 9D). The 23.9 times reduction in CO_2 production may be due in part to inhibition by the higher doses of biochar. In the bench scale semi-continuous experiment, the fine walnut supplemented digesters had an 83.0 percent methane content which equates to a 1.7 times less CO_2 production compared to the control (Figure 11B and 11D). In the pilot scale digesters, the 2nd stage digester with fine walnut had 76.6 percent methane content for the first 35 days of the experiment which equates to 3.3 times less CO_2 production compared to the PC (Figure 13B and 13D). Overall, there was 3.1 times less CO_2 production in the 2nd stage digester supplemented with walnut biochar compared to the PC.

Furthermore, a recent study conducted by Argonne shows that the biochar addition resulted in a biogas stream with a H_2S concentration below method detection limit (<5 parts per billion), compared to the control digesters (H_2S 90 parts per million (ppm)).[33] The limitation of the coarse walnut biochar due to its larger particle size, lower ash content and divalent cation

31 Vlyssides, A., Karlis, P.K. 2004. Thermal-alkaline solubilization of waste activated sludge as a pre-treatment stage for anaerobic digestion. *Bioresource Technology*, **91**(2), 201-206.

32 Grimberg, S.J., Hilderbrandt, D., Kinnunen, M., Rogers, S. 2015. Anaerobic digestion of food waste through the operation of a mesophilic two-phase pilot scale digester - Assessment of variable loadings on system performance. *Bioresource Technology*, **178**, 226-229.

33 Shen Y, Linville JL, Urgun-Demirtas M, Schoene RP, Snyder SW. 2015b. Producing pipeline-quality biomethane via anaerobic digestion of sludge amended with corn stover biochar with in-situ CO2 removal, *Applied Energy*, **158**, 300-309.

concentration can be seen in the CO_2 sequestration in both batch and semi-continuous experiments as well. In the batch experiment, the coarse walnut biochar only sequestered 83.2 percent of the CO_2 compared to the fine walnut biochar (Figure 9D). This is contrary to theoretical calculations based on the ash percentage and cation concentration which indicate that the coarse walnut biochar should have a higher CO_2 sequestration ability. In the Argonne's pilot scale semi-continuous experiment, the coarse walnut biochar was used from day 36 to 44. For the first 36 days of the experiment, the 2nd stage walnut supplemented digester maintained average methane content of 76.5 percent despite an increase in OLR. However, when the biochar was switched to the coarse walnut biochar, the methane content quickly fell to a low of 71.5 percent. After a 4-day recovery period, the methane content returned to an average of 75.6 percent for the remaindered of the experiment. This results in an average 3.3 times reduction in CO_2 production compared to the PC with the fine walnut biochar and only a 2.7 times reduction in CO_2 production with the coarse walnut biochar indicating that particle size plays a large role in the dissolution of cations from the biochar surface.

Impact of Biochar Addition on Digester Performance

While high biochar dosage increases methane content in the biogas, it can result in toxicity in the digesters; therefore, the biochar dosage is an important parameter to optimize for this process. In the batch experiments, the FW10 and FW20 digesters had a decreased methane yield compared to the PC digester (Figure 8C and 10C). This may be due to the high calcium and magnesium concentrations in the FW10 digesters (average 2300 mg/L and 630 mg/L, respectively) being inhibitory (Figure 7A and 9A). However, the calcium and magnesium concentration was lower in the CW10 digester (1500 mg/L and 440 mg/L, respectively) leading to a smaller reduction in methane yield compared to the PC digester (Figure 7C). Although the potassium concentration was higher in the CW10 digester (average 2360 mg/L) than the FW10 digester (average 1800 mg/L), the concentration is below the reported 5800 mg/L inhibitory concentration.[34]

Based on the analysis of the performance results obtained in the batch study, the biochar addition rate was selected for the semi-continuous experiments. The biochar was added at a dose of approximately 3-3.5g biochar for the batch experiments. The final concentration of cations in the bench scale 2nd stage FW digesters reached 3200 mg/L calcium, 580 mg/L magnesium and 1550 mg/L potassium. By adding the biochar daily with the organic food waste, it is possible that the bacteria were able to adapt to the high cation concentrations allowing for high CO_2 sequestration without any inhibition in the methane yield (Figure 11C). The pilot scale digesters did not follow the same trend for the calcium and magnesium concentration increase over the course of the experiment. The calcium concentration decreased over the course of the experiment and the magnesium concentration remained constant. This may be due to better biochar removal from the digester with daily effluent

34 Chen, Y., Cheng, J.J., Creamer, K.S. 2008. Inhibition of anaerobic digestion process: A review. *Bioresource Technology*, **99**(10), 4044-4064.

volumes. The digester configuration was limiting for the homogenous distribution of biochar in the digester for the bench scale experiment allowing for a layer of biochar to form at the top of the digester liquid level above the effluent sampling port opening. For the pilot scale digesters, a 3rd impeller was placed at the top of the digester liquid level to assist in incorporating the biochar into the digester media more efficiently.

The alkali and alkaline earth metals also lead to high buffering capacity of the biochar-amended digesters, which will enhance the process stability as compared to the control digester. The fine walnut amended batch digesters had a total alkalinity concentration 1.9 – 2.7 times higher than the PC digester. The total alkalinity concentration increased by 2.3 times in the FW10 digester compared to the total alkalinity increase of 2.1 times in the CW10 digester. The total alkalinity concentrations in batch digesters amended with 10g walnut biochar and higher were above the desirable range (2000-5000 mg/L). However, in the two-stage semi-continuous experiments, the total alkalinity was 2.6 times higher than the PC in the bench scale digester and 1.6 times higher for the pilot scale digester which was in the desirable range for a successful AD process.

Conclusion and Recommendations for Field-Scale Digester Tests

This project presented a novel process utilizing mineral-rich walnut biochar for food waste AD with in-situ CO_2 sequestration, improved process stability and reduction of costly and energy intensive biogas cleanup and upgrading process. We designed and operated pilot-scale digesters utilizing the CleanWorld's AD criteria. The fine walnut biochar proved to be superior to the coarse walnut biochar in both batch and semi-continuous operation. This process produced a methane yield of approximately 550 mL CH_4/ g VS_{added} for both the biochar amended digesters and the PC digesters. This process is able to sequester up to 3.3 times less CO_2 compared to the PC by increasing the methane content by 1.15 times. More importantly, this process furthers the development of new sources of renewable fuel production by creating a process for producing biomethane efficiently. It is recommended to conduct further field-scale testing of this process at ARP's digesters in order to determine optimal process conditions.

CHAPTER 3: Field Demonstration of the Additives at American River Packaging

Design Demonstration Equipment for ARP

CleanWorld designed the pilot digester at ARP with the intention of loading clean feedstocks with minimal need for preprocessing. The digester was run on source-separated food waste from grocery stores for over nine months in order to prove out the AD system. Subsequently, the digester was loaded as needed for conducting research. For the current project, the feedstock will be a high-liquid hydrolyzate from another CleanWorld AD system loading source-separated organics. In addition, a dry additive amendment will be added to improve the performance of the AD system. This report will describe the engineering considerations and changes made to the existing digester in order to accommodate the current research.

Receiving and Loading Subsystem

The ARP feedstock receiving and loading system consists of a stainless steel hopper atop an auger system for metering feedstock into a wet hammer mill (Figure 17). The hammer mill is fitted with a screen for reducing feedstock particle size and a liquid injection system to wet the material being loaded. Valves allow for selecting process water or fresh water as the injection liquid, and the process water can come from either the first or second tank in the system.

Figure 17: ARP Receiving and Loading Subsystem

Source: CleanWorld

In addition to receiving feedstock through the hopper/auger, liquid feedstocks can be injected directly into the front-end of fluid transfer skid which can direct the feedstock into any of the four tanks in the system. In practice, feedstock is loaded into the first tank. For this project, this will be the loading method utilized as the feedstock will be pre-hydrolyzed liquid slurries from our SATS AD system. In order to ensure smooth, fast delivery of feedstocks, the loading system was modified to accept a four-inch hose by adding a tee to the existing four-inch pipe leading from the outlet of the hammer-mill pump. A knife-gate valve on the pressure side of the pump will be closed during loading to prevent backflow of feedstock into the hammer mill. The end of the tee was fitted with a valve and a quick-connect (cam-lock) fitting for connecting to the feedstock hauling tanks as they arrive. Feedstock loads were accepted from 6,000 gallon tanker trucks that were filled at the SATS AD site. The full 6,000 gallon feedstock batch was loaded in less than one hour at the ARP site.

The existing feedstock loading systems can also be utilized to inject other materials into the system. Liquefied additives could be loaded through the same cam-lock fitting as the feedstock. Solid additives would have to be liquefied and pumped into the system. This could be accomplished via the hammer-mill with either fresh water or process liquid injection from the same tank the material would be loaded into. Alternatively, a separate pre-blending tank could be added for liquefying the additive and pumping it directly into the system, as is done with liquid feedstocks. Testing was conducted to determine the best method.

Feedstock Loading

The existing feedstock loading system was bypassed for this study. A tee was added with a four-inch cam-lock fitting to allow pumper trucks to discharge directly into the main intake of the transfer skid (see Figure 18). A knife gate valve was closed to isolate the grinder/hopper and prevent back-flow. The pumper trucks delivered feedstock every Thursday. The material was hauled from another digester facility with a large separation system where the feedstocks were ground, slurried, and pre-hydrolysed before being hauled to ARP for loading. A three-inch gas-powered trash pump was rented for emptying the tanks at ARP and pumping the material into the digester. No additional engineering changes were required for loading material into the digester.

Figure 18: Feedstock Loading into Digester

Source: CleanWorld

Additive Loading

Biochar was sourced from the Dixon Ridge Farms gasification system on Putah Creek Road, Winters, California (west of Sacramento). Dixon Ridge operates a walnut shell fed gasifier; the Biomax 100 manufactured by Community Power Corporation that produces two grades of biochar: fine and coarse. The biochar is removed from the gasifier via auger (see Figure 19) and loaded into bags lining a plastic bin. One consideration was how to haul and pack the biochar.

Figure 19: Gasification System at Dixon Ridge Farms Producing Walnut Biochar

Source: CleanWorld

The plastic bags used to pack the fine biochar were old and dusty (see Figure 20). Some were beginning to degrade. There was concern that the fine, dusty material would not be secure in the back of a truck. Furthermore, if hauled to ARP, handling the material could be an issue.

Figure 20: Dixon Ridge Farms Biochar Storage Center

Source: CleanWorld

The average weight of the bags was 65 – 75 pounds. A one-ton load would then require handling thirty bags. The recommendation from the Argonne researchers was for loading 1,500 pounds per week in at least two loads. An initial test load of 240 pounds (four bags) was received and processed to determine the best method of handling the material (see Figure 21).

Figure 21: Loading Biochar at the ARP Digester: Forklift (Left), Receiving Hopper (Right)

Source: CleanWorld

First, a 65 pound bag of biochar was poured into a vat of water. The biochar repelled the water and floated to the surface. This was probably due to the surface tension around the fine particles. Additional water was sprayed onto the top of the powdered biochar, which dispersed the material, but failed to cause it to mix sufficiently for pumping into the digester (see Figure 22). Significant amounts of dust were also generated during processing.

Figure 22: Pouring Biochar Into Hopper (Left), Dust Control (Middle), Resulting Slurry (Right)

Source: CleanWorld

It was determined that a high shear mixer would be required to liquefy the biochar for loading into the digester. Two options were considered; adding the biochar through a stand-alone mixing tank with a high shear mixing impeller and pump connected to the transfer skid inlet main, or adding the biochar to the grinder/hopper and using the wet hammer mill with recycled process water to slurry the biochar and pump it in via the feedstock loading pump. This latter method was tested first, since the equipment were already present on-site.

The issue with this method was difficulty in transferring the biochar from the plastic bags into the hopper. The advantage of a stand-along mixing tank would be to ergonomically load the biochar at street level without the need for additional equipment. A test was run on the remaining three bags of biochar. Each was lifted above the hopper and cut with a box cutter to allow the biochar to run dry into the hopper. The process liquid return line was connected to the methanogenic tank where the biochar was to be loaded, and the valve was opened to allow the process liquid to flow via gravity into the grinder. The feedstock loading pump was turned on to return the process liquid back into the methanogenic tank. The feed auger was then turned on at a low rate to begin forcing biochar into the grinder where it was mixed with the process water and pumped into the tank. The auger rate was adjusted upward until the grinder began to overload as indicated by the amperage increase and a concurrent change in pitch from the motor. The ideal auger rate was discovered to be about 50 percent of the maximum. At this rate, the three bags of biochar were processed in about an hour (with stops for clearing jams and allowing material to settle).

While this proved to be a tenable method of loading the biochar, it left some room for improvements. The process was slow, with the majority of the difficulty coming from lifting the bags above the hopper. A different bag with a discharge spout and fork-ready handles would greatly simplify the handling and loading of the biochar. CleanWorld recommended to the biochar producer that their material be stored in bulk bags with discharge spouts. Another recommendation was to split the biochar load into three loads per week to ease the labor requirements.

Engineering Recommendations for Implementing Biochar Loading at Full-Scale Digester Facilities

Based on the recommendations of the Argonne researchers to load biochar at a rate of 60 percent of the volatile solids loading rate, a full-scale AD system processing 100 tons per day of food waste (at 20 percent VS) would have to load 12 tons per day of biochar. Aside from the logistics of sourcing 4,380 tons per year of biochar, there would be some major design considerations for loading this quantity of material.

The first consideration would be transport and delivery of the biochar. The largest bulk bags would only hold half a ton, which would mean shipment of over 20 bulk bags per day. At that scale, it would be more efficient to haul the biochar in 20 ton end-dump trucks. Consideration would need to be made for preventing the material from blowing in the wind, given its low density. The hauling trucks would have to be covered, as would the receiving station. CleanWorld recommends an enclosed loading pad so that material could be stored on site and processed without influence from the elements.

The second consideration would be in the design of the processing system. A shear mixing tank with a dedicated return line for process liquid from the methanogenic tank would be required. The system would have to be sized to process up to four days' loading (28 tons) in a single eight hour day (7,000 pounds per hour), in case of holidays and three times per week loading of biochar. Testing to determine the best mixing tank would be required. A ribbon blender would probably be sufficient. However, a tank with a side-mounted mixer could also work. The material would have to be transferred into the mixing tank, which could be executed with a conveyor system, but ease of cleaning would be essential due to the dust level of the biochar. A front-end loaded hopper with an auger into the shear mixer, similar to the system being tested at ARP, would work as long as the dust does not get into the bearings and cause premature wear. CleanWorld would recommend hiring an engineering design consultant with experience in material handling before committing to a design for the biochar loading system.

The current AD system design also does not include a gravity feed line from the methanogenic bioreactor, so an additional process line would need to be added to the material handling skid in order to receive process liquid for mixing with the biochar. This would require additional plumbing and valves integrated with the existing skid. The control system would also need to be modified to accommodate a new transfer routine. Extra labor and maintenance would be added to the operating cost as well. It could take 3-5 man hours per day to load biochar, including time spent receiving trucks, loading the hopper, operating the transfer routine, cleaning, and servicing the extra equipment. All of this will be included in the cost estimates for the process.

Digester Processing Subsystem

The overall digester processing system would not necessarily be changed significantly by the addition of biochar. However, in the lead-up to accepting the material, a few alterations were made to the digester. The data collection and analysis system was upgraded to allow for cloud data storage and recovery in order to simplify the data analysis during the experimental period. The level sensors were changed from radar level sensors to pressure level sensors. Radar level sensors can be influenced by irregularities in the liquid surface that cause erroneous readings. Since the biochar can float, the sensors were changed preemptively to prevent errors in level readings which would potentially allow for overloading of the tanks. Pressure level sensors are immune to these surface irregularities, but they are subject to alterations in the fluid density. However, biochar was mixed with water and the density was measured by weighing a known volume of the slurry. The difference in specific gravity was negligible. The fluid transfer pumps were designed to handle high solids slurries, so no changes were required for the pumps.

Several routine maintenance items were executed in advance of the study as well. Tanks were emptied and inspected. Two tanks were re-coated with epoxy. Upon re-sealing the tanks, pressure testing revealed a leaky pressure relief valve, which was cleaned, re-tested and shown to work well. Pressure testing revealed pitting in the tank roof on one tank. The pits were over-welded to re-seal them, and upon re-testing the pressures were holding. Several pipes, valves, and instruments were also replaced.

For a full-scale AD system processing biochar, the only changes to the core digester processing subsystem would include the installation of a process fluid return line for the biochar loading as described previously. The solids recovery and effluent disposal subsystems would have to be changed significantly, but the ports, pumps, and valves would not need to be changed.

Solids Recovery and Effluent Disposal Subsystem

The biochar added to the digester system are not biodegradable and would not be expected to break down in the digester. As such, the particles would become part of the residuals removed from the digester. In the CleanWorld AD system, residuals are removed at two points in the process. Large solid particulates are removed from the primary methanogenic reactor. These typically are larger than 100 microns in diameter and include coarse undigestible fibers, grit, glass and sand, and plastic shards. The light fraction that floats are only recovered after being thoroughly mixed into the tank, where they can be removed along with the neutrally buoyant and slightly heavy particles that get re-suspended during mixing. The heaviest particles may settle at the bottom and accumulate in the tank slowly until reaching the height of the suction port. Biochar is generally lighter than water, but the extremely small particle size of the fine walnut biochar allows it to become suspended in liquid. As such, it should spread from tank to tank during the various inter-tank transfers. Therefore, it would be expected to also occur in the polishing tank and would eventually wind up in the liquid effluent that is discharged to the sanitary sewer, where it would contribute to the total suspended solids (TSS) content of the wastewater.

Due to the small particle size of the biochar, it is not expected to be captured by CleanWorld's current solid/liquid separation equipment. Nonetheless, a vibratory screen with a 24-inch diameter screen with 50 µm pore size was installed to pre-filter the liquid effluent prior to disposal. The vibratory screen was mounted on a 12-inch steel support foundation with an integrated inlet flow control valve and quick-connect fitting for a two-inch hose from the transfer skid outlet port. The frame was bolted to the concrete foundation next to the sewer inlet. A hose was run from the lower deck discharge port from the screen to the sewer inlet for disposal of the liquid, with a free-fall from the hose outlet to the sewer inlet. Samples could be collected from the hose, and the hose could easily be removed from the sewer discharge and the access port could be capped.

A removable bin was positioned under the outlet of the top deck for recovery and collection of solids. The solids extracted were sampled and analyzed for calculating the mass balance and recovery of biochar. One sample of the liquid recovered was filtered via a membrane separation system, to determine the ability of the membranes to remove the fine biochar silt.

Biogas Processing Subsystem

Biogas from the ARP digester is currently collected via a two-inch manifold where it flows passively through an iron-impregnated carbon absorbent for removal of hydrogen sulfide. From there, the biogas can be diverted to a flare or into a gas processing system for further cleaning and compression. The gas processing system cools the gas to remove over 95 percent of the water vapor and any particulates and siloxanes. It then compresses the biogas to over 80 pounds per square inch gauge (psig). From the outlet of the gas processing skid, the biogas can be diverted to one of two microturbine generators. However, for this research, one of the turbines was replaced with a secondary, low-flow compressor for storing the biogas in a tube trailer that can be transported to other CleanWorld sites. Figure 23 shows the trailer components, clockwise from top left: the wide view of the trailer, the tube storage rack, a close-up of tubes and control system, and the pressure regulator. The tube trailer was sized to hold over 10,000 scf of biogas at 3,500 psig. The four cylinder trailer shown met those specs in a compact package that suited the needs of the research project.

Biogas Compression and Storage for Transport

Figure 23: High-Pressure Gas Cylinder Tube Trailer

Source: CleanWorld

The compressor (see Figure 24) was sized to handle low flows (4 standard cubic feet per minute (scfm)) with an inlet pressure of 0.25 - 5 psig and an outlet pressure of up to 4,200 psig. A small stand-alone unit was sourced that required 230V single-phase power to drive a 3 hp motor and an integrated Programmable Logic Computer controller for automation of start/stop on the unit and temperature compensation during filling. The pressure sensor signal from the AD system was integrated with the compressor’s Programmable Logic Computer so that the compressor could maintain a fixed pressure in the digester by starting and stopping when pressures reached programmable set points. Any excess biogas beyond the capacity of the compressor would be vented to the flare.

Figure 24: Compressor and Flare

Source: CleanWorld

Flare Modifications

In addition to the engineering changes made for compressing and storing the biogas, the flare also had to be modified for the current research. In this study, biogas flow rates of 3 – 7 scfm were expected, which is an order of magnitude lower than the design flows for the flare. In addition, once-per-week feeding of the digester results in transient drops in methane content. Together, these conditions can cause the flare to flame out, especially in high winds. The solution CleanWorld devised involved adding a small natural gas pilot light to the flare (see photo right). The natural gas supplemented methane to the biogas so that even when the flow rate and methane content are low, the flame remains lit. Also, the pilot remains lit even when there's no biogas flow so that the biogas readily ignites when flow returns, despite inclement weather conditions.

ARP Operations Using Argonne Process

The anaerobic digester system at ARP is a patented High Rate Digester (HRD) designed and installed by CleanWorld in 2012 (Figure 25). The system consists of three 30,000 gallon bioreactor vessels and a 10,000 gallon buffer tank for effluent storage and inter-tank transfers. The three tanks serve as a hydrolysis tank, a methanogenesis tank, and a polishing tank and material moves sequentially through the system in that order, converting solids to biogas along the way. The material enters the digester through a front-end loading system consisting of a wet hammer-mill grinder with a hopper and auger for loading materials and a chopper pump for transferring the material to the hydrolysis tank. Biogas is collected via a two-inch gas manifold atop the tanks where it flows to the biogas processing system. Slurry can be pumped out of the digester system via the material transfer skids. These are two interconnected skids designed to integrate the valves, piping, pumps, and controls needed to automatically transfer material between any two tanks in the system or into and out of any of the tanks. These skids represent the core and the brains of the HRD system, allowing for remote access and data logging as well as efficient, low-maintenance digester operations.

Figure 25: Nominal 100,000 Gallon CleanWorld High Rate Digester System Used for Pilot Testing

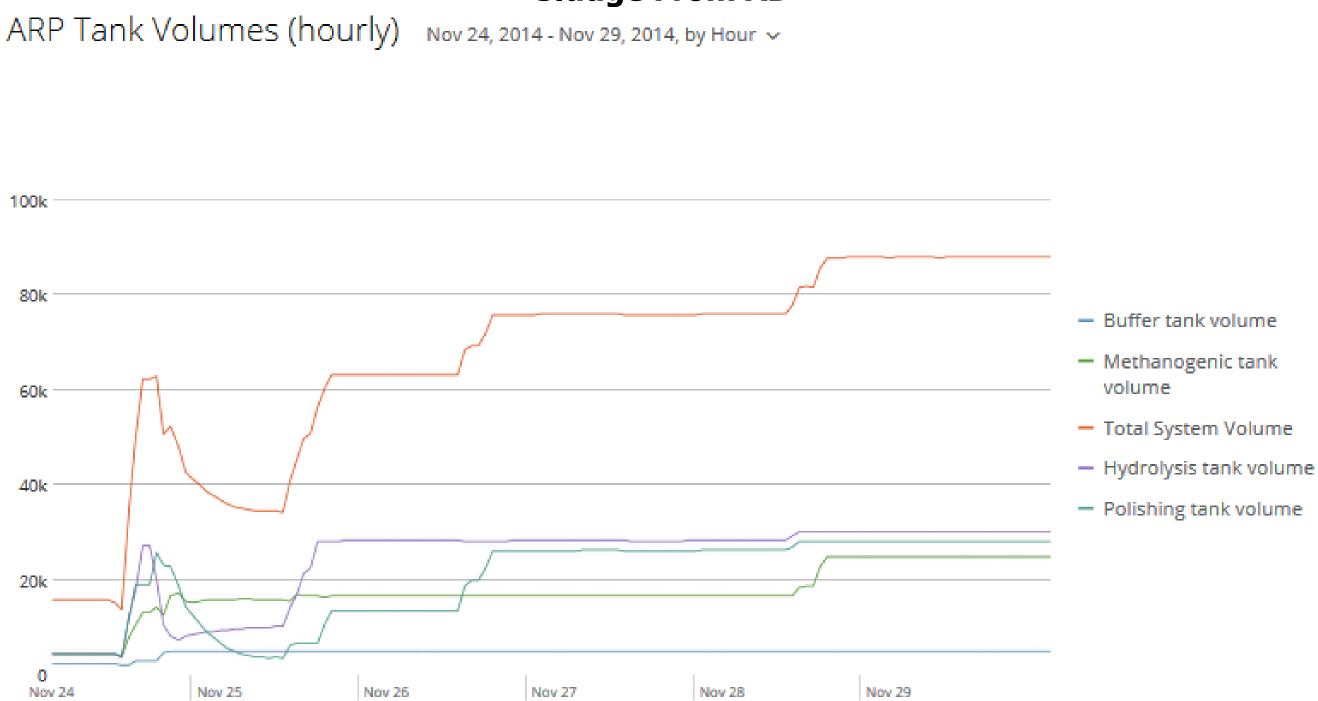
Source: CleanWorld

The ARP digester was operated during the course of this study in order to test the ability of the Argonne additive process to enhance biogas quality and production. The digester was run without the additive for one month to provide a baseline. The additive was subsequently added and the digester was allowed to run long enough to collect substantial data as well as biogas samples for testing of vehicle fuel production equipment.

Digester Loading and Additive Processing

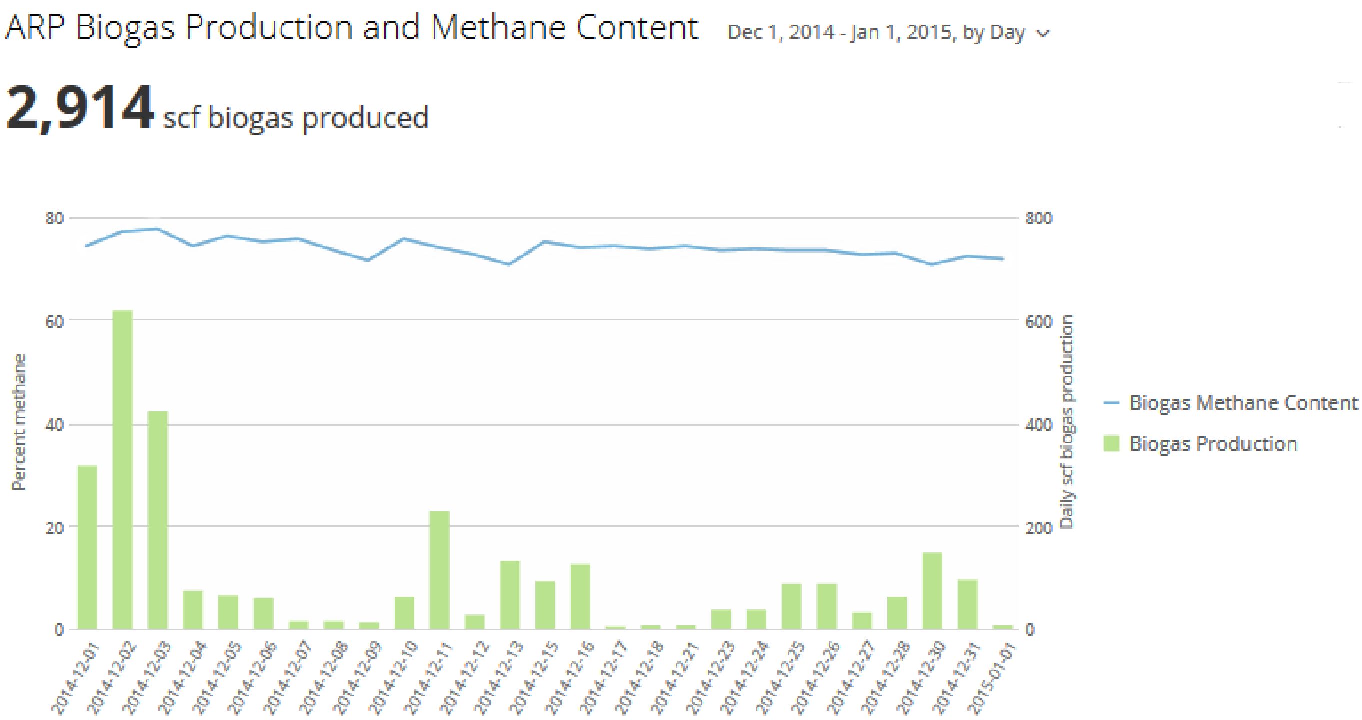
Prior to starting the digester, all of the previous material was removed from the system to ensure a clean digester system for testing. The whole system was inspected and any key repairs were made. A few changes to the system were incorporated as discussed in the Engineering Design Report to accommodate the addition of biochar during the test. Finally, in November, 2014 thermophilic inoculum was added to the system in the form of digester effluent from the operating Renewable Energy Anaerobic Digester system at the University of California at Davis, which is also owned and operated by CleanWorld. The reactor volume during this period is shown in Figure 26. The inoculum was hauled in 6,000 gallon tanker truck loads over a distance of 30 miles and pumped into the tanks via the material transfer skids. In total, 75,000 gallons of inoculum were loaded into the ARP digester to initiate the AD process. The inoculum was allowed several weeks to stabilize and adjust to the new environment before feedstock loading commenced. Biogas production and methane content were monitored during the acclimation period, shown in weekly increments in Figure 27.

Figure 26: Reactor Volume During Initial Inoculation With Thermophilic Seed Sludge From AD



Source: CleanWorld

Figure 27: Daily Total Biogas Production and Methane Content During First Month Post-Inoculation



Source: CleanWorld

Feedstock Loading

Feedstock was hauled weekly in 6,000 gallon pumper trucks from CleanWorld's digesters. The feedstock consisted of pre-hydrolyzed mixed food waste at pH 4.5. Samples were collected and analyzed for TS and VS periodically. Pumper trucks were unloaded directly into the hydrolysis tank, bypassing the grinder. A portable trash pump was rented as needed to extract the slurry from the trucks. In April, the feedstock source was switched from SATS to Renewable Energy Anaerobic Digestion due to operational considerations. The hydrolysate at Renewable Energy Anaerobic Digestion was hauled in one 6,000 gallon tanker truck load per week for use as the feedstock for the ARP digester. Data from the feedstock loading is shown in Table 18, where TS = total solids, VS = volatile solids, TKN = Total Kjeldahl nitrogen, TSS = total suspended solids, TDS = total dissolved solids, and BOD = biological oxygen demand.

Table 18: Feedstock Loading Log with Sample Data

Date	Volume (gal)	Source	TS (mg/L)	VS (mg/L)	VS/TS	TKN (mg/L)	TSS (mg/L)	TDS (mg/L)	BOD (mg/L)
1/14/2015	6,000	SATS							
1/21/2015	4,700	SATS							
1/29/2015	6,000	SATS	41,000	28,000	68%	2,400	NA	NA	NA
2/5/2015	4,800	SATS							
2/12/2015	4,900	SATS							
2/20/2015	4,000	SATS							
2/27/2015	6,000	SATS							
3/6/2015	5,000	SATS	40,000	32,000	80%	NA	NA	NA	NA
3/13/2015	6,000	SATS							
3/20/2015	6,000	SATS							
3/26/2015	5,000	SATS							
4/2/2015	5,600	READ							
4/9/2015	5,500	READ							
4/16/2015	4,700	READ	NA	NA	NA	2,100	23,000	NA	130,000
4/23/2015	5,800	READ	64,000	55,000	86%	NA	31,000	33,000	NA
4/30/2015	5,000	READ							
5/7/2015	5,600	READ	53,000	43,000	81%	NA	NA	NA	NA
5/14/2015	5,500	READ	62,000	50,000	81%	NA	NA	NA	NA
Total	96,100								

Source: CleanWorld

Based on the loading volumes, the final loading rate of the digester approached 3 m^3 per day in 290 m^3 of reactor volume. At an average of 50 kg/m^3 VS, the OLR was 150 kg/d and 0.5 kg/m^3_d. The one BOD analysis run on the feedstock indicated that it contained more BOD than the TS and VS typically indicate. These values are somewhat lower than expected. It is possible that the real solids content of the feedstock is higher than the samples due to the non-homogeneous nature of the samples and the difficulty with collecting samples during industrial-scale loading.

Additive Loading

The additive used for this research was a material byproduct of the gasification of woody feedstocks called biochar. The mineral content of the biochar absorbs CO2 from the gas phase, raises the pH, and provides micronutrients to the bacteria in the digester, making it a potentially beneficial additive for AD. Several sources of biochar were compared by Argonne researchers before deciding upon the source to be used for the study. The biochar ultimately selected came from a gasification facility co-located with a walnut processing facility in Dixon, CA called Dixon Ridge Farms. The biochar used in this study was a fine powder which had been collected from the airborne ash that settled out in a dust collector. While the fine particle size allowed for rapid and thorough mass transfer in the digester, it caused environmental and health hazards that made it difficult to work with in the field.

CleanWorld field workers began adding the fine walnut biochar to the methanogenic tank at ARP in February, 2015 after the digester had been running for over six weeks. An initial 240 pound test load was received and loaded on February 19, 2015. After training staff and making minor changes to the equipment, the biochar was loaded within two hours. A regular weekly load of 1,500 pounds was scheduled to begin the following week. A forklift was rented to facilitate the loading.

Figure 28: Loading of Initial Biochar Test on February 19, 2015

Source: CleanWorld

As shown in Figure 28, the biochar was received in plastic bags that were tied to the tines of the forklift to be raised over the hopper. The bags were then cut to release the biochar which created large plumes of dust. Water was sprayed onto the char to keep the dust down to no effect. Spraying the biochar made the dust plume larger because the surface tension of the particles repelled the biochar. Workers also had to use of full-body protective wear, goggles, and respirator during loading, and these became very dirty during loading, as did all nearby equipment. Initially, the biochar was self-hauled using a rented box truck to contain the broken plastic bags (see photos below in Figure 29), which made loading difficult and dirty. The fine biochar was loaded through March 2015, but in April 2015, a new biochar provider (CoalTec Energy USA Inc) was used to provide a manure-based biochar (EcoChar™).

The new biochar source was analyzed by researchers at Argonne National Laboratory and found to be equally beneficial as a digester additive in terms of chemical composition. The particle size was larger, but this was seen as a benefit for ease of handling. The new source was less costly, cleaner and less dusty, shipped directly to the digester facility, and it arrived in 1000 pound bulk bags with a discharge chute to facilitate loading (see Figure 30). Loading of this material vastly reduced the health and environmental risks due to handling of the material, and it reduced overall cost since the price of the material was about half that of the fine walnut biochar and the labor required for loading was reduced. Ease of processing is as essential to the success of this technology as the physical performance of the biochar.

Figure 29: Biochar Hauling at the Production Facility in Dixon, California

Source: CleanWorld

Figure 30: Biochar Loading with New Source Delivered in 1,000 Pound Bulk Bags

Source: CleanWorld

Digester Operations

The anaerobic digester at the American River Packaging facility began operating in January 2015 and was still operational as of the writing of this report (May 2015). A full digester operating and research plan were assembled to guide operations of the digester. The system is a three-stage, high-solids, thermophilic digester. The substrate used for this research was mixed source-separated food and other organic waste, which was received and processed at another facility prior to transportation to the ARP facility. The trucks used to transport the material pumped the slurried waste directly into the first stage of the digester. Effluent from the digester was discharged to the sanitary sewer directly for disposal. Samples were drawn during each discharge and analyzed per the requirements of the local sanitation district.

The digester was cleaned and refurbished initially in order to ensure adequate operations and to prevent contamination of the system with previous substrates. All three reactors in the system were seeded with a thermophilic inoculum which consisted of effluent from another digester. The inoculation volume was maximized to speed up the start-up time for the digester system. The system was run for one month before the biochar additive begun to be loaded into the digester. During the operating period, data were collected to analyze the performance and health of the system. The digester performed at a high level and the additive appeared to increase the methane content of the biogas.

System Preparation for Testing of Food Waste

Prior to beginning the AD trial, the existing system had to be prepared in order to ensure accurate results. The first step in preparing the AD system for this project involved completely emptying and cleaning the tanks. All of the liquid in the system was filtered to remove large solid particles and the liquid was discharged into the sewer. The solids were hauled to a landfill for disposal. Once the tanks were mostly empty, a vacuum truck extracted the remaining liquid and the tanks were thoroughly rinsed and dried prior to internal inspection by professionals with confined space training.

Once the interior was inspected, it was determined that the walls would have to be sand blasted and the epoxy coating to protect the tank would have to be re-applied. Prior to this, several pinhole leaks in the roof were welded over. Once the tanks were repaired, they were closed and pressure tested to evaluate the presence of leaks. This revealed a gas leak in one of the pressure relief valves which had to be rebuilt.

All of the instruments were inspected and replaced as needed. These included pressure, level, temperature, pH, liquid flow, and gas flow meters. Instruments that were replaced were recalibrated and scaled for accurate readings via the operator interface. Some instruments that were not working properly were removed and sent to the manufacturer for inspection and repair. The digester was operated without non-critical instruments until the units could be repaired or replaced. Some instruments could be serviced on site.

In addition to standard maintenance, parts of the system were upgraded based on prior experience. Pipes that had become clogged during prior operations were replaced with longer sweeps to eliminate sharp turns. New clean out ports were added. Piping that had become damaged was replaced. Faulty valve actuators were replaced with newer, more reliable models. Pumps were cleaned and inspected, but they were found to be intact and required only minimal maintenance.

Upon completion, the digester system was tested as a whole and determined to be fit for full operations. Non-critical items were scheduled for completion after operations had begun. As a result, some of the data were not available for the entire project. However, those missing data points were not critical to the successful operation of the facility.

Operating Plan

The following outline describes the operations and sampling plan initially determined for the project. Ultimately, some of the weekly samples were missed due to unforeseen complications. However, enough of the samples were collected to determine with a high level of certainty the effect of the additive process.

Daily

- Transfer 2,000 gallons per day between each tank
- Recycle to maintain hydrolysis volume at a 6,000 gallon deficit for subsequent loads
- Monitor biogas flow rates and methane content
- Monitor pH, temperatures, and levels of tanks

Weekly

- Load new batch of feedstock
  - 6,000 gallons of pre-hydrolyzed feedstock
  - Sample for TS, VS and TKN
  - Thursday afternoons
- Empty the effluent storage tank
  - ~5000 gallon discharge
  - Test filtration through 50 μm screen
  - Sample for BOD, TSS, TKN, and NH_3-N
  - Thursday mornings
- Load biochar
  - Starting in the third month of operation
  - Four bags of biochar (240 pounds) loaded directly into the methanogenic tank during first load
  - Thereafter, loading 1,500 pounds per week, split into three 500 pound batch loads
  - Tuesday, Thursday, Friday loading
- Sample biogas
  - Before and after H2S removal
  - Analyze CH4, CO2, O2, N2, and H2S

Operational Issues

No unusual operational issues arose during the testing period. The issues that arose were minor and were handled by the CleanWorld maintenance team. These issues included items such as blown fuses, repair of leaky joints, re-calibration of pH probes, replacement of faulty probe cables, and clearing of clogs in the sewer discharge hose. A slightly more serious issue was that the flare pilot flame was extinguished by a period of high winds, which resulted in emission of odorous biogas. The problem was easily remedied, but CleanWorld takes any odor issues very seriously. A shield was constructed to prevent wind exposure which solved the problem, and no further action was necessary.

The only significant operational issue involved loading of the biochar which exposed the operational staff to undue health hazards. Changing the biochar to a less dusty variety and receiving the material in bulk discharge bags helped reduce the health hazard.

In general, the operation of the digester was smooth and did not require excessive labor. Pipes were kept clear of clogs. Sewer discharges were not excessively concentrated. Instruments allowed for good collection of data during the test.

System Performance

The performance of the anaerobic digester system was monitored by in-line instruments that collect data on five-second intervals. These data were available for operator oversight via the on-site operator interface on six and twelve hour local trends. The local trend files were recorded and saved on a server for later evaluation. However, the data from all of the instruments were also recorded in a separate set of files that were downloaded to a CleanWorld server for storage. CleanWorld then uploaded the data files to a cloud service that aggregated the data on five-minute and one-hour intervals. The aggregated data then became available to the cloud service's analytical package which allowed CleanWorld to visualize and process the data as desired.

Some data, such as solids content and compositional analyses, feedstock loading volumes, and effluent discharge volumes and composition were entered into a central database by field operators. A connector to the central database allowed the same cloud service to visualize and analyze the field recorded data.

Overall, the digester performed very highly and achieved high rates of feedstock degradation. The system was loaded once per week, therefore the performance exhibited trademarks of batch loading, even though the process was continuous. The biogas flow rate began high and tailed off toward the end of the week, which methane content suddenly dropped after loading and rapidly increased to a steady-state during the week. Several key events resulted in marked changes in the primary digester performance indicators, such as biogas production rate, methane content, and reactor pH. A list of the key events and their start dates is shown in the table below.

Table 19: Start Dates for Key Events in Testing of Anaerobic Digester System With Biochar Additives

Key Event	Start Date
System inoculation	12-01-2014
Beginning of feedstock loading	01-14-2015
Beginning of biochar loading	02-19-2015
Increase of loading rate and new feedstock source	04-02-2015
Termination of experiment	05-21-2015

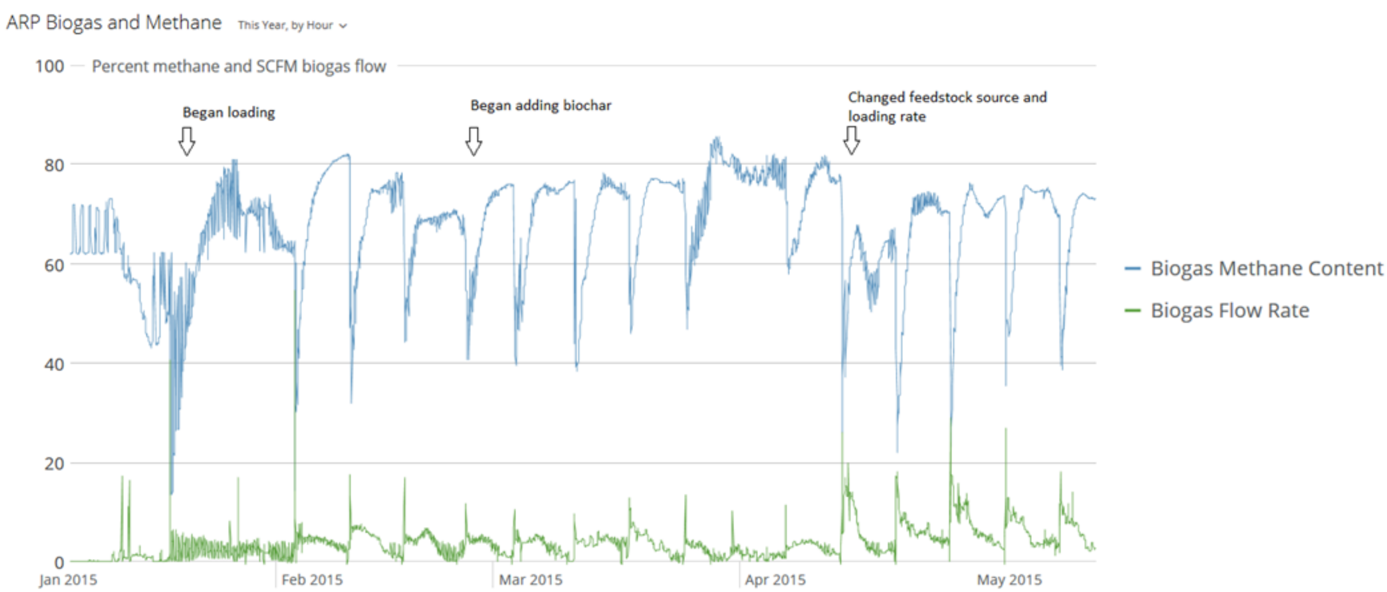
Source: CleanWorld

Biogas Production and Quality

Biogas production commenced immediately upon the beginning of feedstock loading, and methane content was relatively high. However, both flow rate and methane content fluctuated wildly for the first two weeks as the bacteria acclimated to the feedstock (see Figure 31). By the third week of loading, the flows and methane contents had stabilized.

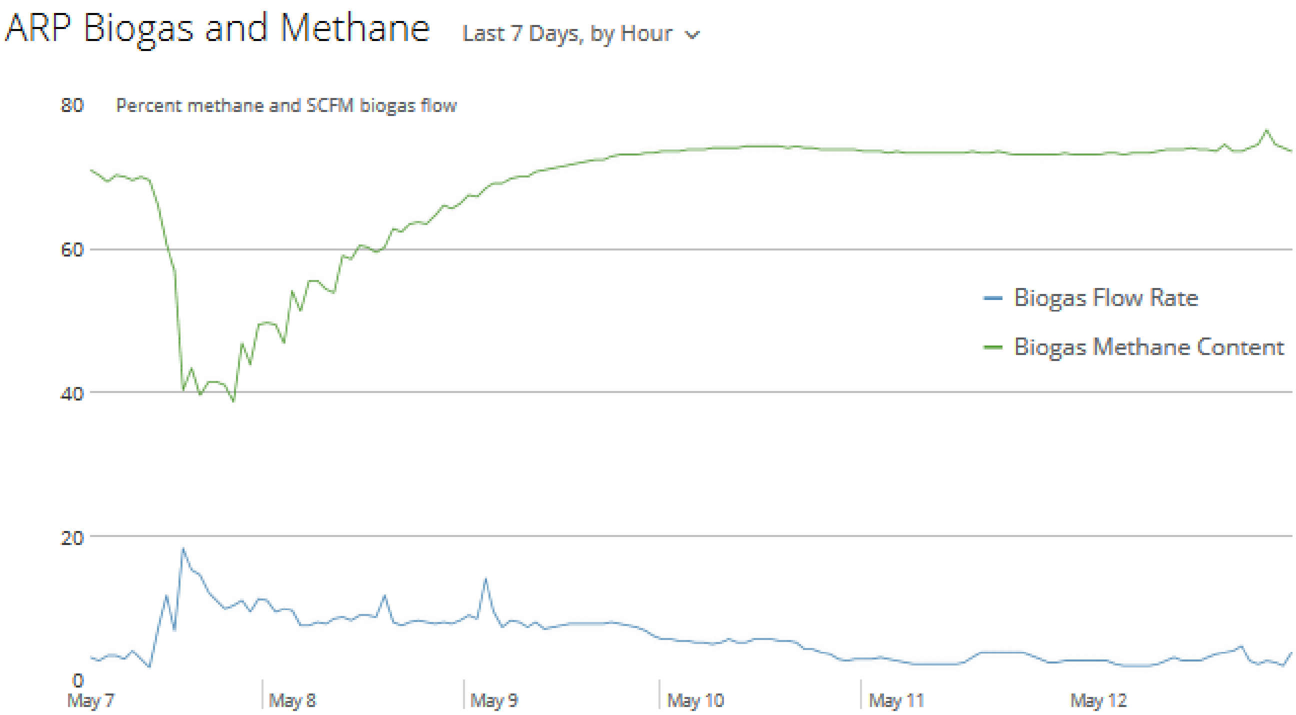
Each batch of loading was marked by a sharp drop in methane content, followed by a slow rise culminating in a relatively steady methane content 2-4 days after the batch load. Initially, methane content dropped to as low as 14 percent, although after two weeks the lowest methane content was >40 percent. The steady-state methane content before adding biochar was 70 percent. After the first biochar load the steady-state methane content was 76 percent. By the fifth week after biochar loading began, the steady-state methane content was 79 – 81 percent. However, when the loading rate was subsequently increased, the steady-state methane content dropped to 65 percent and the initial dip returned to lower levels (22-26 percent) for the first three weeks. The steady-state methane content returned to 73-75 percent within a week, but the previous highs of 80 percent were not seen again. It should be noted however, that high loading rates typically result in lower methane content as more hydrolysis takes place. Furthermore, the biochar loading was not increased concomitantly with the loading rate, although the biochar loading was still within the recommended guidelines provided by Argonne researchers based on the substrate concentration. The biochar loading may have been lower than recommended if the VS loading rate were higher than expected. There was a drop in methane content at the higher loading rate which could have been due to the low loading of biochar.

Figure 31: Biogas Flow Rate (scfm) and Methane Content (percent v:v) Throughout the Trial Period



Source: CleanWorld

Figure 32: Typical Batch Curve for Biogas Flow Rate and Methane Content. Feedstock Loaded On May 7

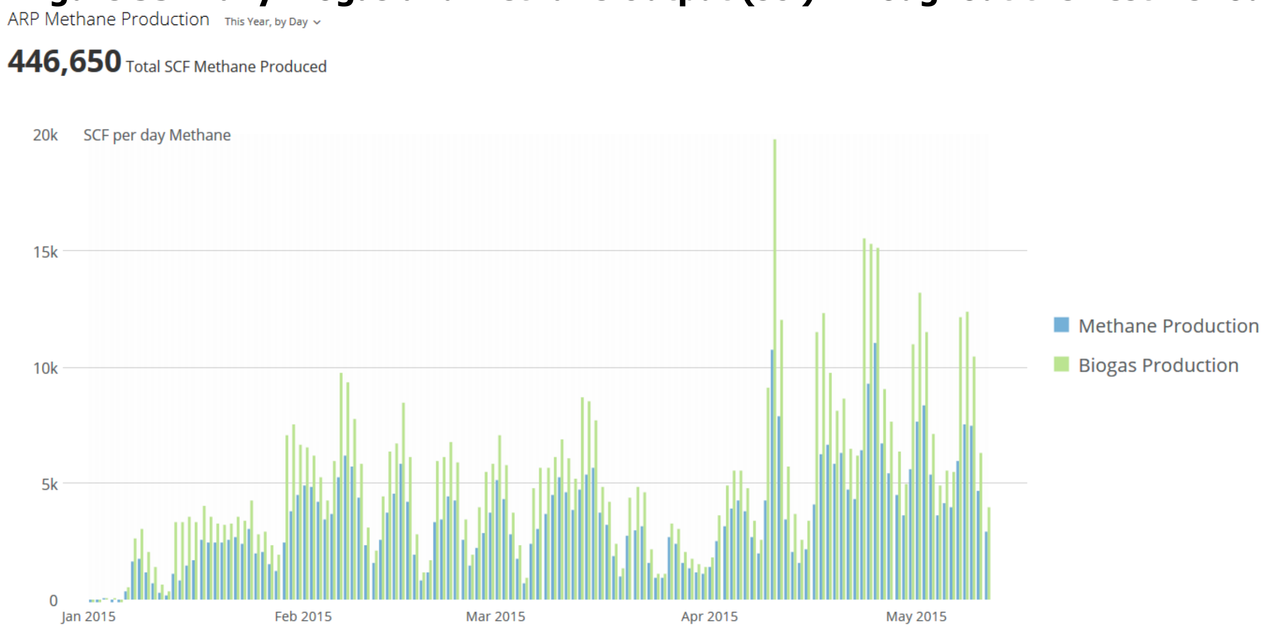


Source: CleanWorld

Although the methane content was lower in the beginning, the biogas flow rate was higher (see Figure 32). Therefore, the overall methane output varied less than the biogas production, as revealed by Figure 33 below which shows daily biogas and methane output in scf. Integration was based on the sum of the products of hourly average flow rates and methane contents through the day. Biochar loading did not appear to augment the overall biogas or methane production. It only increased the mean methane content of the biogas produced. This was true whether aggregating hourly, daily, or weekly. This is consistent with the mode of action of the biochar being limited to the adsorption of CO_2 from the gas phase.

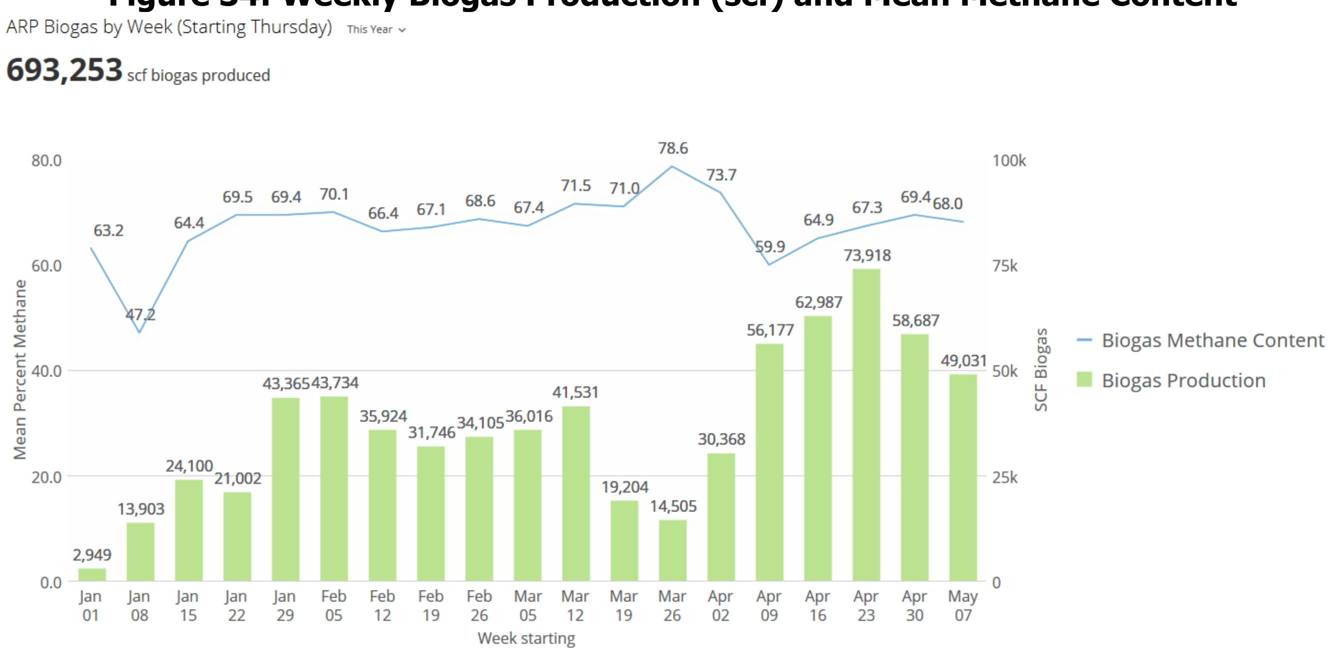
The methane content averaged throughout the week following each batch of feedstock loading was lower than the steady-state methane content (see Figure 34). Before biochar loading, the weekly average methane content was 66 percent. After adding biochar it increased to 71-72 percent with a maximum of 78 percent. After increasing the loading rate, it dropped to 60 percent, but within three weeks was up to 68-69 percent. Increasing the loading rate doubled the biogas production.

Figure 33: Daily Biogas and Methane Output (scf) Throughout the Test Period



Source: CleanWorld

Figure 34: Weekly Biogas Production (scf) and Mean Methane Content



Source: CleanWorld

If the feedstock samples collected represented the overall batch, the ultimate biogas yield at the end of the experiment was approximately 1,500 mL/g VS. However, this is higher than the theoretical limits for the feedstock. This would indicate that the feedstock sample was not truly representative of the overall load, and/or the biogas flow meter was not measuring gas flows properly. At low flow rates, flow meters are known to be less accurate, so this could be a factor since flows were often less than 3 scfm. However, during the last several batches, the majority of the biogas was produced when the flow rates were over 5 scfm, at which point the flow meter readings should have been reliable and biogas yields were still excessively high. Flare operation also indicated healthy biogas flows. Therefore, it is most likely that the feedstock solids concentration was higher than the sample analyses indicated which would reduce the real biogas yield. This could also indicate that the biochar loading rate was lower than it should have been. In any case, the biogas yield was clearly high, which was consistent with the low BOD and solids content of the effluent that indicated complete feedstock degradation.

Biogas flow and methane content was not the only biogas measurement. In addition to the inline biogas analyzer which measured flow rate and methane content, periodic samples were drawn and analyzed using a handheld analyzer fitted with methane, CO_2, oxygen, and hydrogen sulfide sensors. The only major gas components not accounted for were hydrogen (whose concentration should have been very low because the measurements were taken at the end of the batch when hydrolysis was at its minimum) and nitrogen. Therefore, the balance of gas was assumed to be due to the presence of air in the sample. Typically the balance was less than 1 percent, which is normal for biogas when the collection pipe is in good condition. Occasionally the balance was higher. This could have been due to air infiltrating into the sample port through poor tubing seals. More careful samples drawn from a high pressure port with a quick-connect fitting that minimizes air infiltration have never revealed high levels of air in the biogas.

The handheld methane readings generally matched the online sensor reading. The data measuring methane (CH4), CO_2, oxygen (O2), and hydrogen sulfide (H2S) sensors (where the balance is assumed to be nitrogen) is shown in Table 20. The hydrogen sulfide readings prior to removal of H2S ranged week-to-week from 266-1,615 ppm by volume. However, after the H2S scrubber, H2S levels were consistently under the 50 ppm permit limit and typically less than 10 ppm.

Table 20: Biogas Composition as Measured Using a Handheld Meter

Sample Date	CH4 (%)	CO2 (%)	O2 (%)	H2S (ppm)	Balance (%)
Pre-H2S Removal					
3/5/2015	74.0%	26.0%	0.0%	565	0.0%
3/25/2015	79.2%	18.7%	0.0%	612	2.1%
4/9/2015	72.1%	20.1%	1.2%	266	6.6%
4/16/2015	52.7%	35.3%	2.0%	1615	10.0%
4/30/2015	67.0%	26.1%	0.4%	709	6.4%
Post-H2S Removal					
3/5/2015	74.0%	26.0%	0.0%	16	0.0%
3/25/2015	74.4%	24.4%	0.2%	5	1.0%
4/9/2015	76.4%	23.2%	0.0%	4	0.4%
4/16/2015	59.9%	31.5%	1.4%	9	7.2%

Source: CleanWorld

Solids Recovery and Effluent Disposal

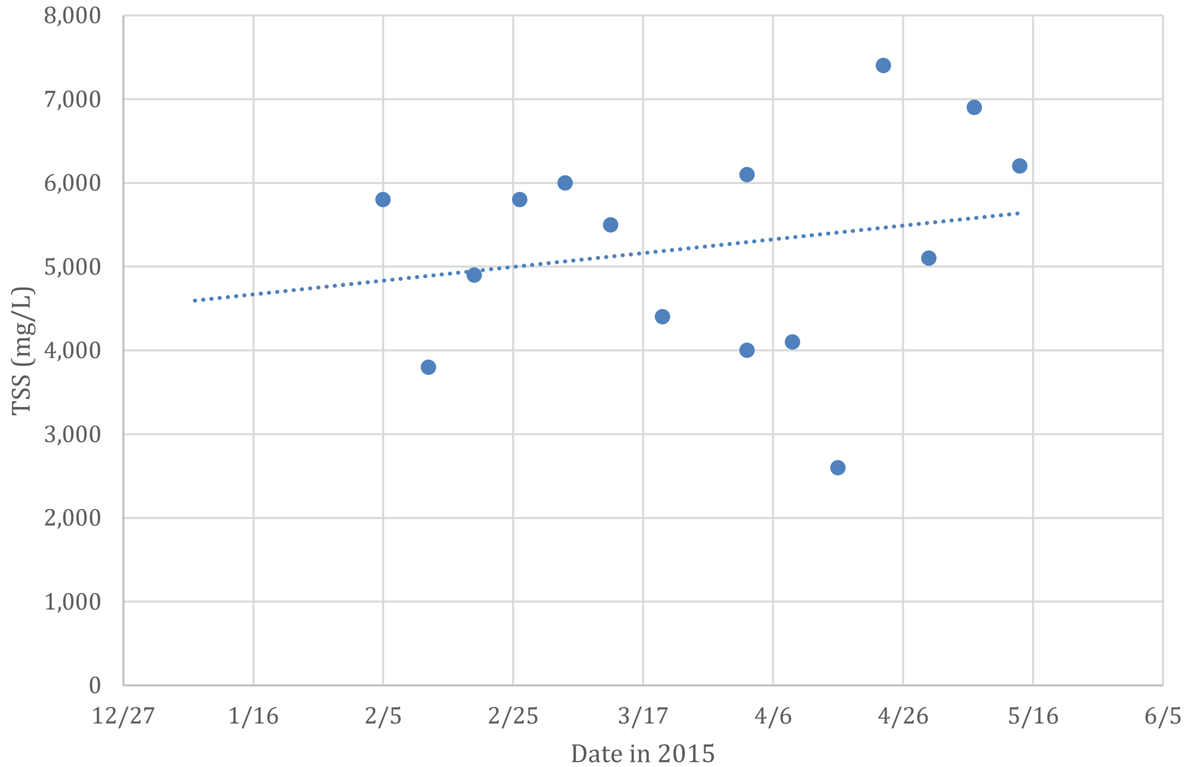
The local sanitation district required weekly analysis of total suspended solids (TSS), BOD, TKN, and ammonia. The results of this analysis are shown in Table 21, detailing total TSS, TDS, five-day biological oxygen demand (BOD), and TKN. The alkalinity units are reported in calcium carbonate equivalents. CleanWorld added alkalinity to the analysis at the beginning of the study to ensure sufficient buffering capacity to begin loading. Over 7,000 mg/L as $CaCO_3$ should provide enough buffering capacity, and the digester exceeded that. The alkalinity was checked again shortly before increasing the loading rate, and again alkalinity exceeded the requirement.

Table 21: Effluent Compositional Analysis

Sample Date	TSS (mg/L)	TDS (mg/L)	BOD (mg/L)	TKN (mg/L)	NH_3-N (mg/L)	Alkalinity (mg/L)	Notes
1/7/2015	14,000	NA	3,800	1,300	1,000	NA	Initial sample
2/5/2015	5,800	NA	1,600	2,600	2,000	8,800	
2/12/2015	3,800	NA	1,200	2,200	1,900	NA	
2/19/2015	4,900	NA	1,200	2,000	1,700	NA	
2/26/2015	5,800	NA	1,100	2,300	1,900	NA	
3/5/2015	6,000	NA	630	2,100	1,700	NA	
3/12/2015	5,500	NA	600	2,300	1,600	NA	
3/20/2015	4,400	NA	780	2,400	1,700	9,600	
3/26/2015	16,000	NA	1,400	1,600	1,300	11,000	
4/2/2015	6,100	NA	1,100	2,400	1,700	NA	No screening
4/2/2015	4,000	NA	1,300	2,300	1,700	NA	With screening (50 µm)
4/9/2015	4,100	NA	1,300	2,300	1,700	NA	
4/16/2015	2,600	NA	1,000	2,300	1,700	NA	
4/23/2015	7,400	NA	1,500	2,100	1,700	NA	
4/30/2015	5,100	NA	900	2,000	2,000	NA	
5/7/2015	6,900	7,800	1,100	2,300	2,000	NA	
5/14/2015	6,200	8,700	840	2,400	2,100	NA	
5/21/2015	5,100	7,800	810	1,300	910	NA	
Average	***6,024***		***1,206***	***2,029***	***1,606***	***1,667***	

Source: CleanWorld

Figure 35: Change in TSS of Digester Effluent Over Time During the Biochar Loading Period



Source: CleanWorld

Through the biochar loading period, the TSS of the effluent did increase very slightly on average, although this trend was weak, in part due to the large variability in TSS measurements, shown in Figure 35 (discarding the outlier on 3/26). A baseline study of the digester found the TSS was 7,867 mg/L which was higher than the TSS reached in this study. In theory, the biochar should not degrade, and therefore should increase the TSS of the effluent, assuming it is not retained within the digester. Since biochar was loaded at a rate of 1,500 pounds per week (97,200 g/d) with a mean substrate flow rate of 5,300 gallons per week (2,870 L/d), the theoretical maximum increase in TSS was 33,868 mg/L. This is orders of magnitude higher than the increase seen during the study. Two possible explanations exist. Some of the particles of biochar may have been so fine that they ended up in the dissolved solids. However, the particle distribution analysis found that over 90 percent of the particles were larger than 63 microns and the cutoff for TSS is 0.45 microns. The other explanation is that most of the biochar had not yet washed through the digester by the end of the study. Since the HRT was 14 weeks and the biochar loading period lasted 16 weeks, this seems to indicate that the biochar was being retained within the digester.

In addition to TSS, TDS was analyzed to determine the TS content of the effluent. Based on the initial loading (~60,000 mg/L TS and 50,000 mg/L VS) the effluent had 25 percent as much TS and as the feedstock. Since no other solids streams were separately collected from the system, this indicates 75 percent TS reduction. BOD of the feedstock was analyzed on one occasion and was found to be 2.36 times higher than the VS concentration. Taking that same ratio, the effluent BOD concentration was indicative of over 99 percent reduction in BOD. This is much higher than typically reported for digester systems. The BOD of the feedstock may be lower than indicated as it is typically 1.2 – 1.5 times as high as the VS concentration. Even at this rate, however, the BOD destruction would be 98 percent, due to the very low BOD of the effluent. The low loading rate and resulting long HRT may be allowing for nearly complete consumption of the digestible material. At higher loading rates, the effluent BOD would be expected to increase. Other CleanWorld facilities have reported over 10 times as high BOD in the effluent at higher loading rates.

On 4/2/2015, a small-scale vibratory screen with a 270 mesh screen (50 µm pore size) was utilized to pre-filter the effluent as a test to determine the feasibility of recovering biochar and reducing the TSS load disposed to the sewer. The screen was found to remove about 2,000 mg/L TSS which reduced the TSS by 35 percent. Based on this, screening 6,000 gallons during the weekly discharge would recover about 100 pounds of suspended solids. Even if all the suspended solids were biochar, that only represents 6 percent of the biochar loaded. As mentioned previously, the TSS did not increase significantly during the study, indicating that very little of the biochar was passing through the digester. Because the TSS reduction, biochar recovery rate, and flow rates through the screen were low, and the additional labor cost required to operate the machine was high, this was not continued as a regular operation. In a full-scale facility, other separation technologies with higher flows and recovery rates could greatly reduce the cost of the biochar process and may be worth considering.

Conclusions of Additive Addition on Biogas and Overall Digester Performance

Overall, the CleanWorld anaerobic digester did an excellent job of converting the feedstock to biogas at exceedingly high degradation rates during the course of the study, regardless of additive addition. The biogas yield was close to the maximum possible for the feedstock, and the resulting effluent was extremely low in BOD and residual digestible solids. The methane content of the biogas was high throughout the experiment, but the addition of biochar appeared to increase the steady-state methane content by five to ten percentage points (from 70 percent to 75-80 percent methane by volume). The weekly average methane content also increased by a similar amount (from 66 percent to 71-78 percent). This effect was attenuated by higher loading rates, but the ultimate methane content of the biogas was still higher than typical.

The additive process did not appear to increase the overall biogas or methane production rate or yield. However, the biogas yield was close to the theoretical maximum and may not have had much room for improvement. The effect of biochar on the ability to sustain higher overall loading rates was not tested, but the pH was higher than normal throughout the experiment. Therefore, there may be some reason to believe that the biochar could help achieve higher overall OLRs and maintain digester stability. In an unpublished, informal study, CleanWorld found that biochar was able to restore biogas production when a reactor was inhibited by high acidity. It required more biochar than hydroxide to restore the pH to neutral, but the pH was more stable after adding the biochar. However, biochar is a more costly pH adjustment additive than other forms of hydroxide.

Overall, biochar appeared to be a beneficial additive. It boosted the methane content of the biogas, and it may have other benefits such as improved digester stability at high loading rates and enhanced value to the solid residuals. These latter benefits require additional testing. The price of biochar may need to decline significantly, however, for the benefits to outweigh the costs. CleanWorld recommends the following continuations of this research:

1. Studying the ability to capture and recycle biochar from the effluent as a means of reducing the overall cost of the additive process
2. Evaluating the agronomic benefits of the effluent with biochar as compared with typical digester effluent without biochar
3. Determining the effect of biochar additive on the stability of the digester at very high OLRs

The next component of this study will be to evaluate the effect of the increased methane content on the downstream biogas processing equipment.

CHAPTER 4: Biomethane Testing and Clean Up to Fuel Quality Methane

Biogas is the biologically derived gaseous product of the AD process. The gas consists primarily of CO_2 and methane, both of which are decomposition products of the AD biological pathways. These make up over 95 percent of the volume of the biogas, but the balance can contain hydrogen sulfide (a product of the biological decomposition of sulfurous compounds in the absence of oxygen), hydrogen gas (a byproduct of the biological hydrolysis process), nitrogen and oxygen (usually due to infiltration of air into the biogas pipeline), and various trace compounds and elements that typically diffuse from the aqueous medium into the gas phase. The most insidious of these is siloxane, which is a man-made compound containing silicone that readily diffuses into the gas phase and can damage equipment when combusted. Other trace constituents of concern are volatile organic compounds that result from decomposition of organic matter but diffuse at very low rates into the gas phase, microbial cells, heavy metals, other sulfur compounds, amines, and particulate matter. The presence and significance of these and other trace constituents are currently being debated and studied in depth by several agencies.

Biogas can be used to produce electricity and/or heat, in which case the CO_2 is an inert constituent that can pass through most conversion systems during the combustion process. However, when utilizing biogas for transportation fuel, energy density becomes important. Therefore, the CO_2 is removed and the resulting gas will consist of over 95percent methane, at which point it becomes chemically identical to natural gas. However, because the methane purified from biogas came from carbon that was part of the short-term natural global carbon cycle, the resulting product is called renewable natural gas (RNG), which can be compressed for injection into high-pressure vessels just like conventional, non-renewable, compressed natural gas (CNG).

CleanWorld has performed extensive testing of the composition of RNG produced at SATS facility. The gas cleaning apparatus employed by CleanWorld has consistently produced RNG that meets several key standards for transportation fuels and specifically CNG. This RNG has been shown to be cleaner than conventional pipeline natural gas with regard to several constituents. CleanWorld has also been participating in a large, in-depth study on the composition of RNG that will analyze several unusual compounds that are not currently monitored under the existing standards. Because of the thoroughness of the analyses performed by CleanWorld as well as the excellent track record of the RNG produced, this study based its evaluation on the same equipment used by CleanWorld at SATS.

The biogas upgrading system used by CleanWorld was developed by BioCNG™ LLC for the production of transportation-grade RNG from biogas and landfill gas. The system involves several sequential steps, including hydrogen sulfide removal, moisture removal, siloxane and other impurity removal, and finally CO_2 removal. Hydrogen sulfide removal is technically required for any biogas use and therefore it can be considered to be separate from the

BioCNG process, although the BioCNG processing skid does employ H2S removal as a first step. CleanWorld uses a passive bed adsorption method of stripping H2S from biogas. Other methods such as biological conversion introduce air into the biogas which can dilute the gas with nitrogen (the oxygen is consumed in the biological oxidation of H2S), and this dilution becomes problematic when producing transportation fuel since it reduces energy density. Moisture is removed from the biogas by cooling the gas and condensing the moisture in the gas. This is an important step since the CleanWorld digesters operate at high temperatures which increases the saturation level. Vehicle specifications for moisture in the natural gas fuel are very strict. Moisture removal is an often underappreciated step in the purification of biogas, and it consumes a lot of energy. Removal of siloxanes and other trace contaminants occurs via a passive adsorption system, which is sufficient for the low levels of these contaminants in the gas. To remove CO_2, the BioCNG unit compresses the biogas and passes it through a molecular sieve. While there are many methods, this was found to be the most cost effective given the scale of the system needed for processing the quantities of biogas typically produced by CleanWorld's anaerobic digesters. Molecular sieves can produce extremely pure RNG at a wide range of flow rates. However, they are not particularly efficient at capturing all of the methane in the biogas. While this means that some of the available methane is lost during the conversion process, it also means that the rejected gas (or "tail gas") from the BioCNG system is readily combustible in a traditional flare. This makes emissions controls extremely simple, as the same flare used as a fail-safe can also be used to burn the tail gas.

The primary factor determining the recovery rate of the BioCNG biogas purification system is the methane content of the biogas. Therefore, since the biochar additive process tested as part of this research project greatly affected the methane content of the biogas, it should alter both the methane recovery rate of the purification system as well as the methane content (and combustibility) of the tail gas. In general, increased methane content results in a greater recovery rate and lower tail gas methane content. Therefore, much of the potential economic benefit of the additive process depends on understanding how the changing methane content affects methane recovery and tail gas methane content.

The goal of this study was to evaluate the effect of biogas composition on BioCNG efficiency and performance in order to inform a thorough economic study of the production of transportation fuel from biogas enhanced by the additive process.

Preparation and Execution of Biogas Clean-up Testing

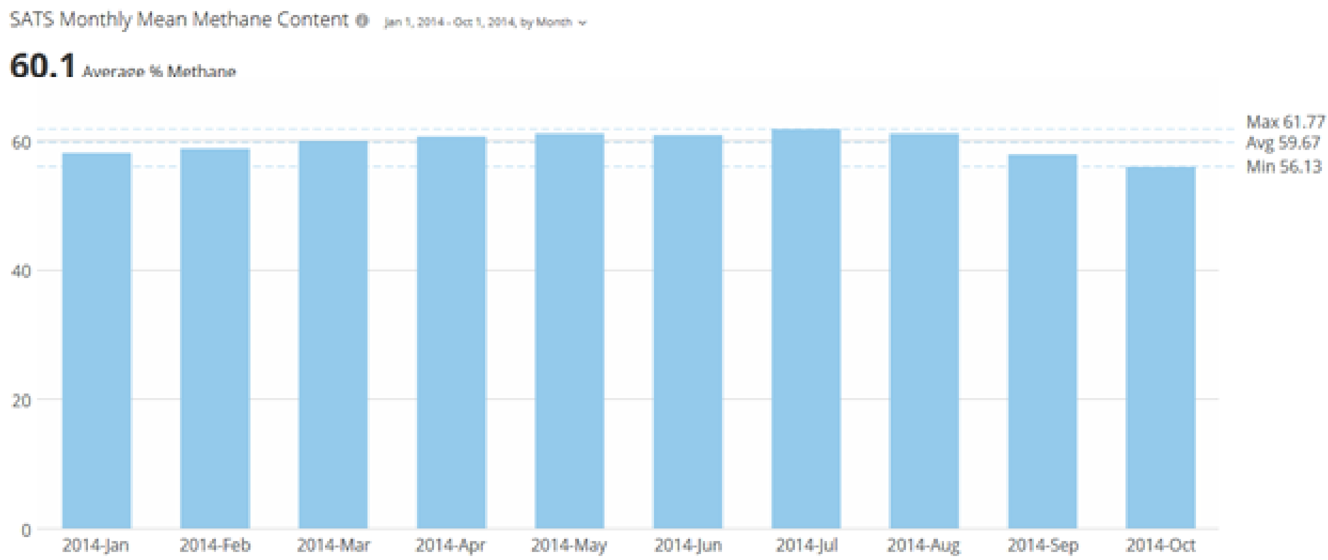
Initially, CleanWorld planned on transporting a biogas sample 30 miles from the testing facility to the facility that houses the biogas cleaning equipment in order to process the sample and collect data. Due to the size of the processing equipment, it was determined that 10,000 scf of biogas would be required to run the test equipment for 3 hours, which would provide just enough time to reach a steady-state and collect samples for analysis at a third-party lab. Due to the large volume, the only feasible method to transport the sample would be to rent a tube trailer with capacity for high-pressure gas storage (3,600 psig). CleanWorld identified an equipment provider with pre-fabricated trailers with low enough weight to be towed with a light-duty truck. The biogas would then have to be compressed from less than 1 pound per square inch (psi) up to 3,600 psi into the 10,000 scf gas cylinders in the trailer. At the flow rates typically seen from the digester (3-5 scfm), it would take several days to fill the cylinder.

Upon searching for low flow compressors suited to processing biogas and capable of continuous duty for several days, it became clear that the application was unique in the industry. No appropriate compressor could be located. In addition, the compressor would have to be integrated with the existing biogas processing system and controls would have to be added to allow for the continuous compression of a variable flow with a fixed flow unit. There was also a good chance that the first test could fail for numerous unforeseen reasons, and a second or third test would have to be run. Finally, the information to be gained by performing this scale of field trial was minimal. The goal of the experiment would be to determine what effect the increased methane content in the biogas would have on the performance and costs of biogas cleaning and upgrading. CleanWorld has processed biogas in the past with a wide range of methane contents, and the equipment manufacturer has performed extensive research on this very question. Because the scope of the work required for this small test was larger than anticipated and the equipment required was fundamentally unavailable, it was decided that sufficient information could be gained by providing the existing data on biogas quality to the manufacturer of the biogas cleaning and upgrading equipment (BioCNG). CleanWorld contracted their engineers to provide a detailed evaluation of the cost and performance of the technology when processing biogas with the average composition seen historically at the SATS where the equipment is installed and comparing it with the biogas composition seen during this study. The results of this analysis are presented and interpreted here.

Sample Analysis and Results

Monthly, daily, and hourly methane content at the SATS digester was evaluated during a period of healthy digester operation from the first half of 2014 in order to obtain a realistic estimate of the biogas methane content. At that time the average monthly methane content was 56 – 62 percent with an overall mean of 60 percent, which was used as the base case for this analysis (Figure 36). It should be noted that over that same period of time the daily average methane content varied from 51 – 71 percent, therefore the biogas cleaning system was operated over a wide range of methane contents.

Figure 36: Mean Monthly Biogas Methane Content at the Sacramento Biodigester



Source: CleanWorld

At the end of the biochar additive study when the bacteria had acclimated to the feedstock and the batch loading, the steady-state methane content was 73-75 percent during each of the last three weeks. The monthly mean ranged from 67 – 73 percent, but due to the restricted time frame of the study, this is not a reliable measure because there were many transient changes in methane content. The predicted average methane content when at steady-state over a longer period of time with the biochar additive was 74 percent, which was the value used to compare the biogas with and without biochar additive.

In addition to the biogas methane content, the average flow rate modeled for application of biochar additive at the 100 tons per day Sacramento Biodigester facility was 300 scfm. This is the maximum processing capacity currently installed. While the facility has the capacity to also generate electricity from biogas in excess of 300 scfm, for the purposes of this analysis it was assumed that electricity would have to be purchased.

Effect of Additive Process on Biogas Clean-Up and Processing Equipment

For the purposes of assessing the effect of the additive process on biogas clean-up, historical data on the performance of the cleaning system in use at SATS were provided along with the methane content data from the biochar trials to the system manufacturer (BioCNG, LLC). They provided estimated system performance details if the same process were applied at the SATS facility after it reaches its full production capacity (300 scfm mean biogas output). For the purpose of the analysis, it was assumed that the biogas flow rate would remain the same whether or not the biochar additive were used. At the bench scale, there was no net increase in methane yield despite a clear increase in the methane content. This suggests lower biogas flow rates with biochar. However, at the pilot scale, there was no clear effect of biochar on the biogas flow rate. Since the SATS digester is expected to produce in excess of 300 scfm biogas when at full capacity, even though the biogas upgrading equipment has a maximum throughput of 300 scfm, even if the overall biogas flow rate were slightly lower with the biochar, it can be safely assumed that the biogas upgrading equipment would still be operated at its maximum capacity.

Biomethane Production and Quality

The biogas cleaning system is based on the performance of a specially designed membrane manufactured by Air Liquide. The capabilities of these membranes have been extensively modeled by the manufacturer, resulting in the precise ability to predict the performance based on assumed inputs. For the baseline scenario, biogas was assumed to consist of 60 percent methane, 1 percent nitrogen, and traces of H2S and water vapor remaining after the primary removal of these contaminants. The balance of the gas was then assumed to consist entirely of CO_2. The biogas flow rate was modeled at 300 scfm (See Figure 37 Top). After adding biochar, the composition of the biogas was assumed to shift to 74 percent methane. The trace gasses were assumed to remain the same and the balance was assumed to be CO_2 again (see Figure 37 Bottom).

Figure 37: Estimated Biogas Cleaning Membrane Performance: no Additives (Top), add Biochar (Bottom)

AIR LIQUIDE MEDAL

Component	Raw Feed	Compr Disch	Feed 1	Permeate 1	Residue 1 / Sales Gas	
	mol%	mol%	mol%	mol%	mol%	
CO2	38.8898	38.8898	38.8898	71.5537	5.0	Btu/SCF
CH4	60.0000	60.0000	60.0000	27.5914	93.6	948
O2	0.0000	0.0000	0.0000	0.0000	0.0000	Wobbe
N2	1.0000	1.0000	1.0000	0.6395	1.3741	1217
H2S	0.0013	0.0013	0.0013	0.0022	0.0004	
H20	0.1089	0.1089	0.1089	0.2132	0.000629	
	100.0000					
Flow (SCFM)	300	300	300	153	147.3	
Flow(MMSCFD)	0.432	0.432	0.432	0.220	0.212	
Avg Flow Including PSA Repres/Depres (MMSCFD)		0.438				
Flow(Nm3/H)	482	482	482	246	237	
Recycle Ratio						
		System Feed				Plan on Outlet
Pressure (PSIG)		100.0	100.0	1.0	96.87	60.0
Pressure(bara)		7.908	7.908	1.082	7.69	
Temperature(°C)		5	22			
Dew Pt (°C)				-13		
% CH4 Recovery					76.6%	
				Local Baro		
				14.7		
	# of elements					
Stage 1:	3.0	4240				

AIR LIQUIDE MEDAL

Component	Raw Feed mol%	Compr Disch mol%	Feed 1 mol%	Permeate 1 mol%	Residue 1 / Sales Gas mol%	
CO2	24.8898	24.8898	24.8898	59.6184	5.0	Btu/SCF
CH4	74.0000	74.0000	74.0000	39.3395	93.9	950
O2	0.0000	0.0000	0.0000	0.0000	0.0000	Wobbe
N2	1.0000	1.0000	1.0000	0.7457	1.1458	1221
H2S	0.0013	0.0013	0.0013	0.0028	0.0005	
H20	0.1089	0.1089	0.1089	0.2937	0.002935	
	100.0000					
Flow (SCFM)	300	300	300	109	190.7	
Flow(MMSCFD)	0.432	0.432	0.432	0.157	0.275	
Avg Flow Including PSA Repres/Depres (MMSCFD)		0.438				
Flow(Nm3/H)	482	482	482	176	307	
Recycle Ratio						
		System Feed				Plan on Outlet
Pressure (PSIG)		100.0	100.0	1.0	96.39	60.0
Pressure(bara)		7.908	7.908	1.082	7.66	
Temperature(°C)		5	22			
Dew Pt (°C)				-9		
% CH4 Recovery					80.6%	
				Local Baro		
				14.7		
	# of elements					
Stage 1:	2.9	4240				

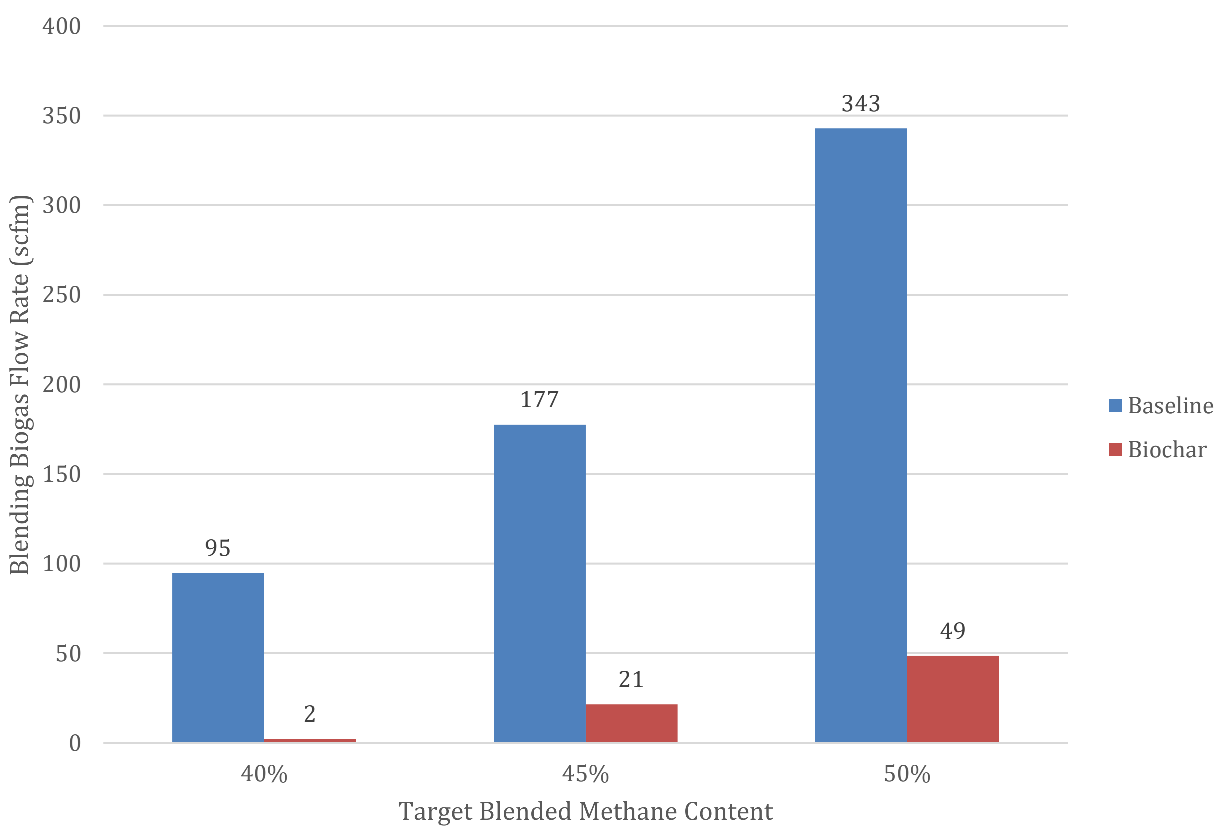
Source: Air Liquide

The primary difference between the base case and the biochar scenario was the methane recovery rate, which went from 76.6 percent to 80.6 percent from the base to the biochar scenario. This represents a 5.2 percent increase in the ability of the membranes to capture methane in the biogas. In addition, because the methane content was higher but the biogas flow rate was equal in the biochar scenario there was 23.3 percent more methane available for capture to begin with in the biochar scenario.

The net result was that the biogas cleaning equipment would be expected to produce 29.5 percent more biomethane (190.7 versus 147.3 scfm) after adding biochar. Another result would be that 28.8 percent less tail gas (the gas rejected by the membranes) would be produced, and that tail gas would have a higher methane content (39.3 percent versus 27.6 percent) due to the lower original CO_2 content of the biogas. This would make the tail gas more valuable as a fuel source.

These differences can easily translate into economic differences, since the value of the biomethane is well defined. Currently, the tail gas has no value because it is flared. However, it is reasonable to consider recovering some value from the tail gas when it has a higher heating value to begin with. For example, many generators operate on landfill gas with 40-45 percent methane. It would not require blending much biogas to raise the methane content of the tail gas to the minimum threshold level of the generator (see Figure 38).

Figure 38: Quantities of Biogas Needed for Blending to Create Various Target Fuel Methane Contents



Source: CleanWorld

Under the base case, the minimum amount of biogas needed for blending with tail gas to produce a fuel with 40 percent methane would be 95 scfm. Therefore, the system would have to produce 395 scfm in total, which is more than was projected for the given quantity of feedstock, and the generator would then have to be tuned to run at 40 percent methane which is at the lowest end of its capabilities. With biochar, however, only 321 – 349 scfm of biogas would have to be produced in order to produce a blended tail gas with 45-50 percent methane, which would easily allow the generator to operate.

The SATS digester was originally estimated to produce enough biogas to generate about 130 kW with the biogas available in excess of the 300 scfm needed for biomethane production. Adding the tail gas would increase the electrical production potential by about 280 kW. This would potentially eliminate the digester's parasitic electrical needs and offset a portion of the gas compression system's power demand. Again, the economic value of the additional electricity is easily estimable. However, significant costs would be associated with installing the blending equipment and controls as well as the additional generating capacity. Since the SATS facility already has a 190 kW nameplate capacity generator, the added blending equipment and controls would allow the facility to run the generator more continuously, but it would only add 70 – 100 kW electrical production. The rest of the tail gas would most likely still need to be flared.

CHAPTER 5: Distribution of Biomethane as a Transportation Fuel

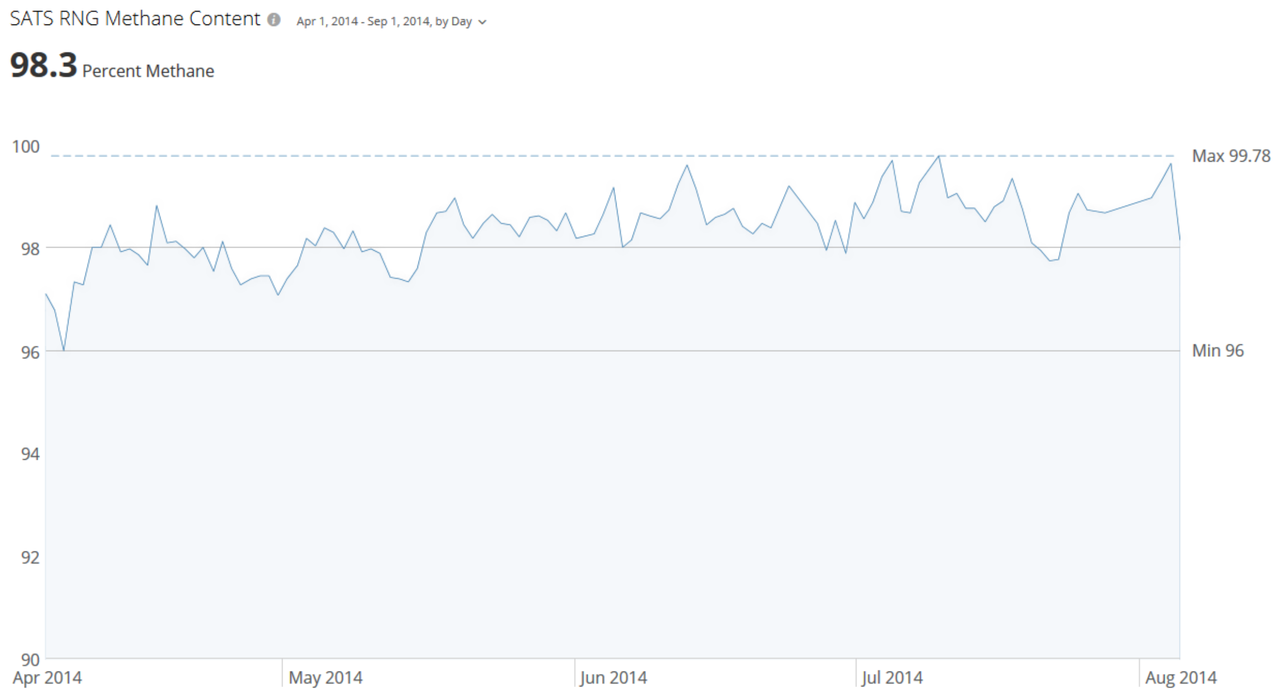
The goal of this task was to demonstrate the feasibility of storing and distributing biomethane as a transportation fuel. Biogas is routinely cleaned, compressed, stored, and then injected into vehicles at the SATS where CleanWorld and Atlas Waste hauling have partnered on a CNG vehicle fueling system. Since launch, the Sacramento Biodigester has sold over 46,000 therms of biomethane to Atlas for fueling vehicles. In addition to storing and distributing biomethane, for this project CleanWorld also considered compression, storage and transportation of biogas from the test facility at ARP to the facility that houses the biogas cleaning and upgrading system at SATS.

Collection and Distribution of Biomethane as Transportation Fuel

CleanWorld operates the anaerobic digester and the biogas processing system to generate clean biomethane at 90-100 psi. This gas is delivered via a direct pipeline connection to a low pressure storage vessel, via a booster compressor that pressurizes the clean biomethane to 250 psi. A larger compressor then compresses the biogas up to 3,000 – 4,000 psi for high pressure storage prior to vehicle injection. Heavy duty vehicles and busses can fill their cylinders from one of four pumps and quickly refill their tanks with the high pressure gas. The fueling system will preferentially refill the high pressure storage vessels with biomethane until the low pressure vessel’s internal pressure drops below a setpoint, at which time conventional natural gas is then added to the high pressure storage tank to make up any lag in biomethane production relative to the demand.

CleanWorld has developed a strict protocol for sampling and analysis of the biomethane to ensure fuel quality. An online CO_2 analyzer monitors the RNG fuel quality (see Figure 39), which averages over 98 percent methane. The biogas cleaning unit can be adjusted in increase or decrease the CO_2 content of the biomethane based on the rejection factor of the membrane. However, nitrogen and oxygen in the biogas due to air infiltration cannot be rejected and will dilute the methane content.

Figure 39: Typical Methane Content of RNG Produced at the Sacramento Biodigester from Biogas



Source: CleanWorld

The Cummins engine specification (20067 chemical composition) requires that the overall methane content of the RNG remains above 90 percent, hydrogen sulfide must be below 6 ppm, and siloxanes must be below 3 ppm. CleanWorld regularly tests the RNG for methane, CO_2, hydrogen, nitrogen and oxygen, hydrocarbons, sulfur compounds, volatile organic compounds, and siloxanes. The results of the tests are reported to the customer, and none of the samples tested has failed to meet the engine specifications. In addition, one sample of conventional natural gas was also tested for comparative purposes, and the RNG was as clean or cleaner than the conventional CNG with regards to sulfur compounds.

Compression and Storage of Biogas and Biomethane

The original strategy for this study was to compress biogas at the ARP facility and transport it to the SATS facility where it could be processed through the biogas cleaning system. CleanWorld did extensive research on equipment required for this purpose, which was informative for biogas and biomethane storage and transport.

Initially, it was determined that in order to perform a significant test of the cleaning system on the biogas produced at ARP, a long run of the equipment would be preferable. The smallest BioCNG biogas cleaning and upgrading system required a minimum feed-gas flow rate of 50 cubic feet per minute of biogas. Therefore, a storage system for a minimum of 10,000 cubic feet was sought in order to provide at least three hours of continuous testing. The equipment evaluated would also serve for storage of clean biomethane and could be filled from the same filling station used to fill heavy duty vehicles. A trailer with 10,000 cubic feet of storage would have the capacity to provide 78 diesel gallon equivalents to heavy-duty vehicles. This would fuel 400 – 700 miles of heavy-duty vehicle driving. Since the trailer could be hauled with a light-duty truck, this would be an efficient method of topping off stranded vehicles and providing fuel to remote locations.

Compressed biomethane could also be used to fuel a generator during peak periods. Ten thousand cubic feet of biomethane would generate 700 - 1200 kWh of electricity, depending on the conversion efficiency of the generator. At the SATS facility, the 190 kW generator has an assumed conversion efficiency of 35 percent, which would produce 1,025 kWh from 10,000 cubic feet of biomethane. It would take about 5 hours to consume the full 10,000 cubic feet of biomethane. Therefore, the compressed biomethane could extend the generator run-time by 5 hours, which would help buffer lulls in biogas production.

At the ARP facility, compression of biogas was also evaluated. The biogas flow rates seen during the study varied from 3 to 7 scfm. They fluctuated hour to hour as well as day to day with the lower flow rates coinciding with the higher methane contents. Thus, the ideal time for compressing the biogas would be several days after loading the digester. However, at that time biogas flow rates would be tailing off. Therefore, compressors were sought for biogas compression at a relatively low fixed flow rate. However, the digester would have to produce more biogas than the compressor could handle or else an automatic intertie to the pressure sensor would be required to shut down the compressor when the digester pressure became too low.

Low flow, high pressure compressors were difficult to find. The home vehicle fueling industry was found to produce some compressors designed to fill vehicles with pipeline natural gas overnight. These were designed to compress 1 – 2 scfm feed gas flow rates, which would be less than the digester produced, even at the end of the week. At a compression rate of 2 scfm, it would take 83 hours to fill a 10,000 cubic foot tube trailer (3.5 days). Compression could begin three days after digester loading and complete before the next batch of feedstock was loaded. This would maximize the methane content of the biogas during compression. However, home vehicle fueling compressors were not rated for continuous duty. Many included automatic safety shut-off controls to prevent continuous compression of gas in case of leaks. These would only allow the compressor to operate for part of a day before being reset, and it would void the warranty to override the automatic shut-off or run the compressor continuously.

In addition, these compressors require dry gas without hydrogen sulfide, therefore the biogas would have to be dried and de-sulfurized. Raw biogas would not be suitable for compression. The existing hydrogen sulfide removal equipment would provide sufficient desulfurization, but active moisture removal would be required as well. Standard gas desiccators designed for low moisture gas would not be suitable because they would saturate too quickly for use with biogas at 10 – 15 percent moisture content (by volume). CleanWorld considered utilizing the existing gas processing system at ARP which removes hydrogen sulfide, siloxane, and moisture prior to injection into the microturbine. This could have met the gas conditioning requirements, but the conditioning system would also compress the gas to 90 psi. The low flow compressor was designed for low pressure gas (0.25 psi), so a regulator would have to be used capable of stepping down from 90 to 0.25 psi. Such regulators are very costly. It may have required multiple stages of pressure regulation.

Controlling the gas flow rate would also be challenging. The biogas processing system was designed for flow rates of 30 scfm. An internal recycle could be used to provide sufficient gas to the compressor without pulling biogas from the digester faster than it was produced, but this would waste electricity and overly wear the compressor. In addition, if the low flow compressor required a steady flow rate of biogas, any extra biogas produced by the digester would have to be shunted to the flare, or else the digester pressure would increase. A modulating valve would have to be installed and controlled to maintain the digester pressure within a certain range. This valve would have to allow fine control of flow rates with rapid response to fluctuating flows. The controls system would have to be built and installed with a programmable logic controller for reading pressures and modulating valves accordingly. The logic would have to be written, installed, tested and verified prior to use. It would likely have to be adjusted after installation to meet the needs of the changing flows of the digester.

Due to the complexity of the process, the escalating cost of the installation, and the lack of certainty that the system would work as intended or that it would generate the data required (three hours of run-time would not provide much room for error or the development of steady-state operations), the project team decided not to move forward with the planned compression, storage, and transportation of biogas from ARP to SATS.

The original SATS biogas processing system did not include sufficient biogas flow meters or methane analyzers for evaluating real-time methane recovery efficiencies from the biogas cleaning system. The newly installed biogas cleaning equipment and biogas controls and monitoring system (part of the system expansion from 25 to 100 tons per day capacity) will make it possible to monitor gas flow rates at the inlets and outlets of each biogas cleaning unit, the flare, as well as the generator. In addition, all of the inlet and tail gas flow rate meters will also provide methane content readings, and the product gas outlet will provide CO_2 content readings. These will provide the ability to track the complete biogas, biomethane, and tail gas mass balance, which will allow for monitoring of the biogas conversion efficiency in real time across a wide range of biogas methane contents. This will ultimately allow CleanWorld to verify the models and adjust them as needed to meet real-world operating conditions.

CHAPTER 6: Commercialization Plan

Argonne's deliverables for the Task 7 Commercialization Plan include their Engineering, Economic and Environmental Analysis of Additive Technology

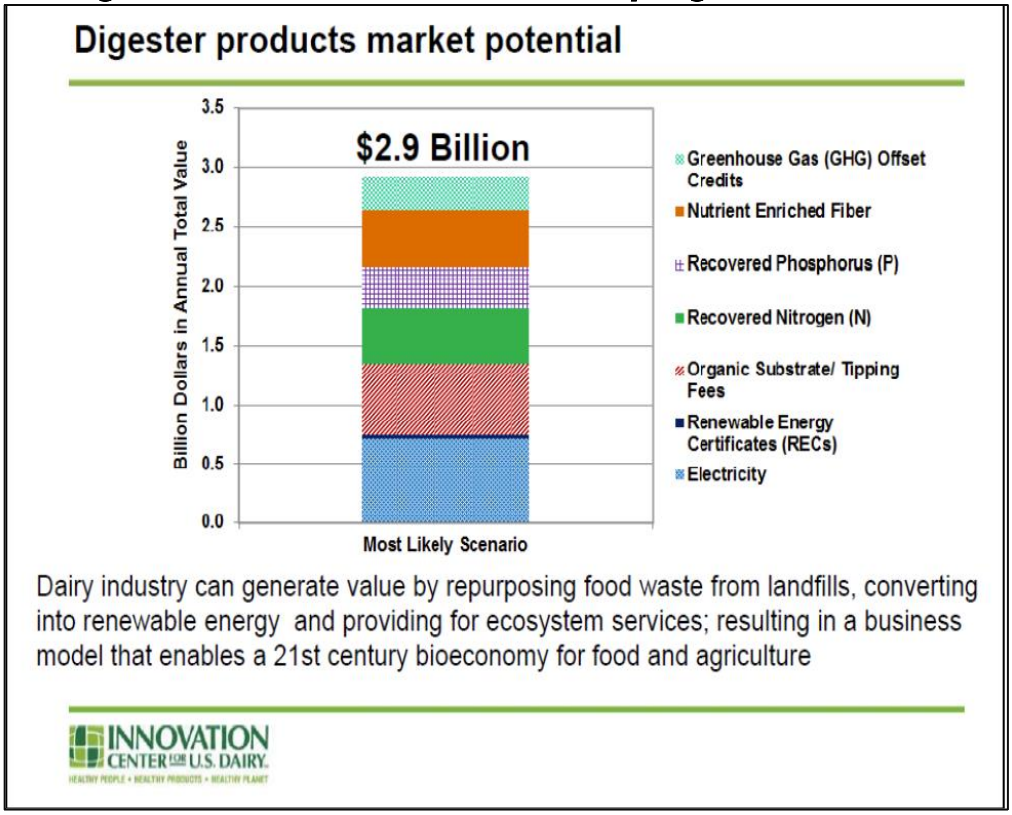
Market Evaluation for Biochar

There is a need for development of a more advanced technoeconomic assessment model to include environmental, technical, and economic performance data from production of high value co-products, reduction in nutrient and GHGs, and water quality benefits in addition to production of biogas from AD of food waste. Without consolidation of this data in the technoeconomic analysis, the return on investment in digesters for only energy production remains low to negative. This is consistent with the current conditions of biogas industry in the U.S. The estimated internal rate of return ranges between 12-65 percent if economic and environmental benefits of digester co-products are included as shown in Figure 40.[35] This will not only provide a better understanding of utilization of AD technology, but also increase market size for application of the technology in the digestion of organic waste streams. As discussed before, the digestate from the biochar supplemented digester includes more nutrients than that of conventional AD operation. The technoeconomic analysis of the additive technology should therefore include both realizing the nutrient and environmental benefits of digestate as well as economic sustainability of the additive technology.

---

35 Innovation Center for U.S. Dairy. 2013. National Market Value of Anaerobic Digestion Products. Prepared by Informa Economics.

Figure 40: Market Potential of Dairy Digester Products



Source: Innovation Center for the U.S. Dairy, 2013

Recently biogas from landfills, WWTP digesters, agricultural digesters, and separated municipal solid waste has been qualified by the U.S. EPA as a new pathway for cellulosic and advanced fuel development under the Renewable Fuel Standard. This action is expected to promote production of biogas-derived renewable fuels and the generation of Renewable Identification Numbers, which will accelerate the development of sustainable and viable biogas industry. USDA estimates that in 2010, approximately 133 billion pounds of food from U.S. retail food stores, restaurants, and homes were not consumed and were mostly disposed into the landfills. According to the recent US biogas roadmap, the nationwide adoption of AD technology can produce a total potential energy of 2.5 billion gasoline gallon equivalents per year and reduce emissions by 6.5 million metric tons of CO_2 equivalent per year in the US. California could generate about 284 billion cubic feet of biogas per year from AD of organic waste which is equivalent to 10 percent of total gas consumption in California.[2]The carbon intensity of gasoline as a transportation fuel is 99.2 grams CO_2 equivalent per megajoule energy while the carbon intensity of biogas from food and green waste is calculated as -15 grams CO_2 equivalent per megajoule energy. Overall benefits from this biogas potential is expected to cut California's GHG emissions by 12.6 million metric tons of CO_2 equivalent per year. Furthermore, both Low Carbon Fuel Standard and GHG offset credits, only specific to California, increase the economic value of beneficiaries of AD of food waste, and hence will encourage the development of a sustainable biogas industry in California.

Biogas is a renewable fuel with multiple potential uses, including on-site power and heat generation, vehicle fuel and, feedstock for liquid fuel and chemicals production. Biogas needs to be treated and upgraded to increase its methane content (approaching 100 percent); the resulting renewable methane is the same as fossil natural gas. Technology selection for contaminants removal and biogas upgrading depends on the gas composition, gas quality specifications for appliances, and grid injection standards. As mentioned before, the cost of biogas upgrading and treatment make up 20-72 percent of the total biogas production process.

Biochar additive technology is not only an adsorbent for biogas cleanup and upgrading, but also a source of micronutrients and alkalinity required for AD of food waste. This is a new paradigm for the application of AD technology as both biogas production and clean up processes take place in the same reaction vessel.[36]

The biochar industry is an emerging industry and has yet to make a substantial entry into large-scale field-scale operations. Most of the business owners are small enterprises which produce relatively small volumes of the biochar and sells the products for local businesses, such as nurseries, greenhouses and small organic farms. Biochar costs are very high and sale volumes are very low since the industry is in the market introduction stage. This is due to the lack of demand relative to the supply of feedstock. However, multi-dimensional utilization of biochar, like soil amendment, activated carbon substitute and byproduct from renewable energy production will establish a strong market for this new product.[37] According to the International Biochar Initiative Survey, the biochar retail prices widely vary, ranging from \$0.08 to \$13.48 per kilogram with an average price of \$2.48 per kilogram.[38] There is a need for deployment of biochar reactors ranging from a few pounds/hr to tons/hr to speed up the establishment of this new industry in the US. Figure 41 shows the relation between biochar market size and biochar value (\$ per ton) for California.[39] According to a recent study, the estimated biochar market size should be 43,500,000 tons/year to sell biochar with a price value of \$100/ton (Figure 42).

---

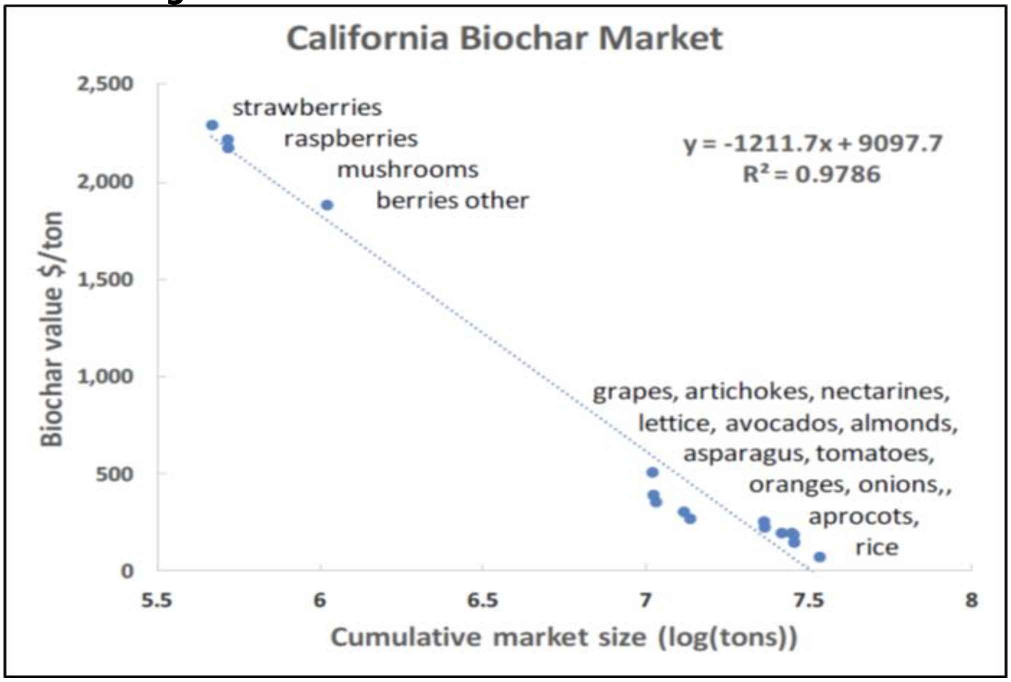
36 Snyder, S.W., Urgun-Demirtas, M., Shen, Y. 2014. Method for generating methane from a carbonaceous feedstock, U.S. Patent Serial No. 14/540,393. Argonne National Laboratory. USA.

37 Whitfield, J. 2013. Getting the Biochar Industry Up to Speed: What Can We Learn From the Pellet Business?, Article from International Biochar Initiative Website: https://biochar-international.org/getting-the-biochar-industry-up-to-speed-what-can-we-learn-from-the-pellet-business/ (accessed December 5, 2019).

38 International Biochar Initiative. 2013. State of the Biochar Industry, International Biochar Initiative State of Industry webpage: https://biochar-international.org/state-of-the-biochar-industry-2013/. (accessed December 5, 2019).

39 Laird, D. 2014. Pathways to Carbon Negative Energy. Article PDF: https://www.biorenew.iastate.edu/files/2014/06/lairdd.pdf.

Figure 41: Biochar Market Value for California

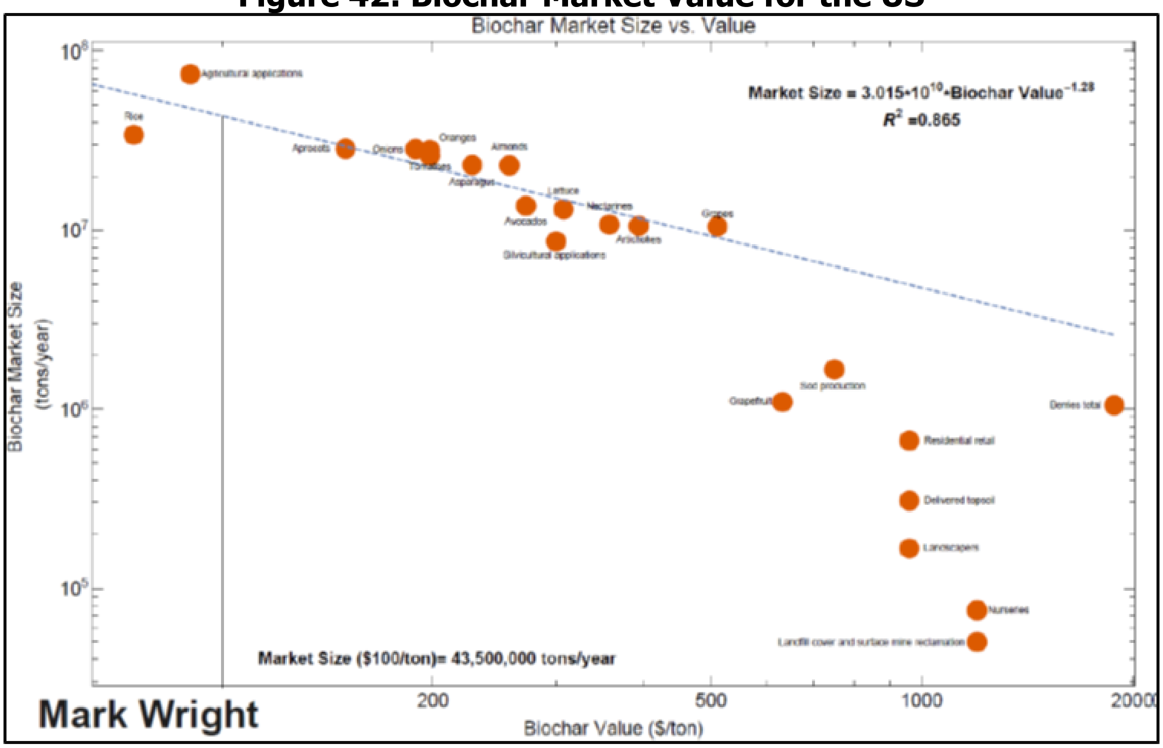


Assumptions: Biochar value/ton= 5 percent of annual crop value/acre

Market size= cumulative crop acres X 10 (10 tons of biochar /acre application)

Source: Laird, 2014

Figure 42: Biochar Market Value for the US



Source: Laird, 2014

The digestate from biochar supplemented digesters has been valorized because of its high fertilizer value. Harvesting these nutrients from the digestate could provide high economic benefits than producing renewable methane production.[35] With the development of ecosystem markets, such as nutrient and carbon credit trading systems, the economic benefits of reduced nutrient and GHG emissions will be monetized further. The U.S. EPA's nutrient credit trading policy[40] creates an economic opportunity and additional income for the AD industry while preventing the flow of nutrient pollution into the natural waterbodies.

Economic Evaluation of Full Scale Implementation of Biochar Additive Process

The costs of adding biochar to the AD process have been well characterized and they are substantial. The goal of this section is to determine whether these costs are justified by efficiency improvements in the downstream processing of the digester.

As discussed previously, the addition of biochar caused an increase in the methane content of the biogas and a decrease in the CO_2 content. The methane content increase was shown to improve the methane recovery rate, which leads to an overall higher vehicle fuel production rate. The decreased CO_2 content was shown to improve the tail gas which could allow for conversion of this otherwise wasted gas stream to electricity and/or heat. Both of these additional energy outputs have well known economic values. The following discussion will attempt to quantify the financial benefit of the extra energy production and then compare it with the cost of the additive process.

One additional effect of biochar on the AD process is on the downstream processing of the resulting digester effluent (assuming the biochar does not accumulate and stay in the digester). However, this effect is unclear, partially because the use of the effluent is unclear. The Sacramento BioDigester where this process is being proposed has historically disposed of all of the effluent to the local wastewater treatment system, where the additional TSS imposed by the biochar would add to the disposal cost of the effluent. This additional cost needs to be quantified.

However, CleanWorld is actively pursuing alternatives to disposal. It could be that one of these alternatives would benefit from the biochar which is also used as a soil amendment in its own right. In addition, biochar could impose additional processing costs depending on the effluent processing system. These costs of difficult to quantify without a specific piece of equipment for empirical testing. A vibratory screen was tested during this study for its ability to extract solids from the digestate, but the biochar did not have any effect as the particle size was too small.

---

40 USEPA. 2014b. Water Quality Trading Policy, EPA webpage for water topics:

http://water.epa.gov/type/watersheds/trading/finalpolicy2003.cfm

http://water.epa.gov/type/watersheds/trading/upload/wri-mrb-trading-report.pdf. (accessed February, 10, 2015).

In light of so much uncertainty, no attempt was made to quantify any economic benefit of the biochar to the effluent and any of the co-products that could be made from it. However, this economic analysis could provide targets for how much value biochar addition would have to add to the downstream effluent processing in order to justify its use, if the energy benefits are insufficient to justify the costs.

Value of Adding Tail Gas to Generator

The economic value of adding tail gas to the existing SATS facility was estimated based on the assumed cost of adding blending equipment, controls and the value of electricity. The average cost of power at the SATS facility ranges from $0.12 to $0.22 per kWh depending on time of day. The average electricity price paid in 2013/2014 was $0.145 per kWh. Assuming the maintenance cost for the generator is $0.015 per kWh (about $25,000 per year), the net cost of electricity used for calculating revenues was $0.13 per kWh.

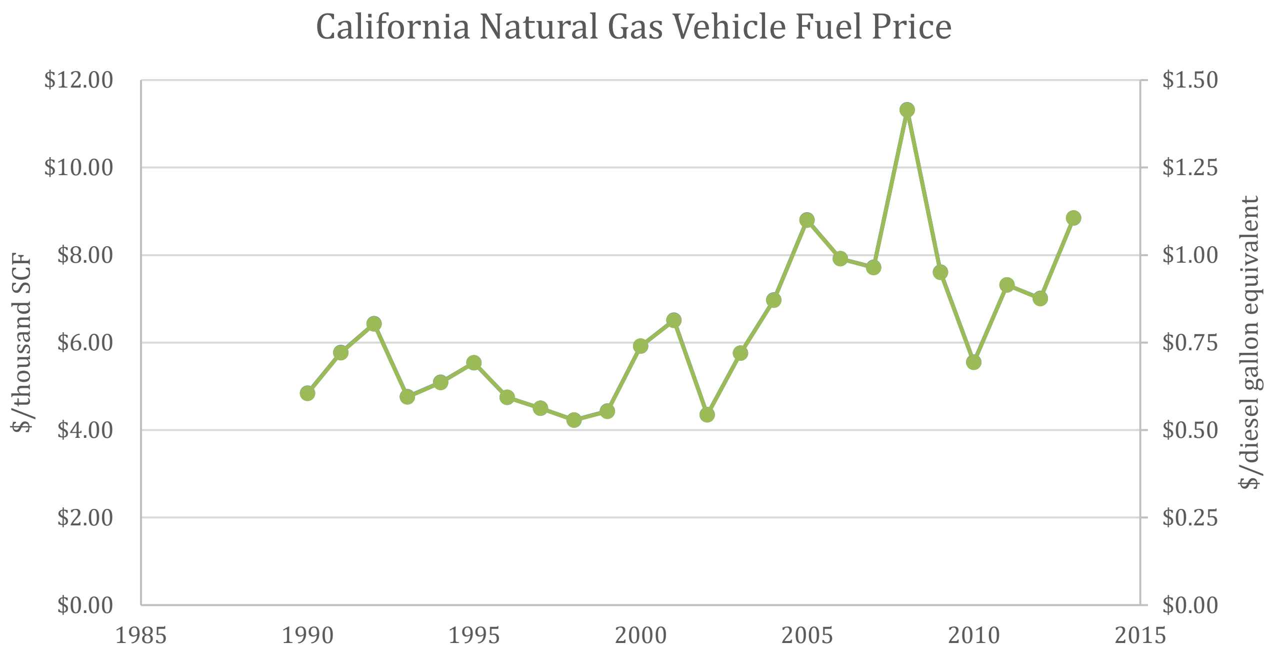
Blending tail gas with biogas would require some piping changes, addition of one or two control valves, possibly a blower, and a control system change. The total cost of the changes would be approximately $60,000 in design, parts, and installation. The added equipment would not be expected to require much maintenance, therefore operating and maintenance costs can be neglected for this. Amortized over the 20-year life of the project, this would cost CleanWorld about $250 per month.

Assuming the generator could run at full capacity with 95 percent availability (including downtime for regular maintenance), the generator would produce $17,784 per month in electricity, which is a net revenue of $17,534 per month. Since approximately 35 percent of that revenue would be due to the addition of the tail gas, the added revenue due to the addition of biochar allowing the consumption of tail gas would be $6,136 per month. However, this particular generator only works well when operating at full capacity due to the nature of the selective catalytic NOx reducer. Therefore, the full value of the electricity could be attributed to the addition of biochar. This would add $210,408 in revenue to the project if considering the full value of running the existing generator at 100 percent of its nameplate capacity with 95 percent availability. If only considering the additional revenue added beyond the expected operation at full capacity, biochar would add $73,632 per year. This revenue would be in addition to any extra revenue generated due to the improved performance of the biogas cleaning system.

Value of Improved Performance of the Biogas Cleaning System

CleanWorld began selling RNG in July 2013. The price of the fuel was pegged to the price charged by Pacific Gas and Electric Company (PG&E) for natural gas. The historical price of natural gas for use as a vehicle fuel has ranged from $4.23 per thousand SCF to a high of $11.32 in 2008 (see Figure 43). In 2013, the mean price of natural gas was $8.85 per thousand SCF. For the purpose of this analysis, the price of RNG was assumed to be $7 - $10 per thousand SCF, or $0.87 - $1.25 per diesel gallon equivalents (assuming a heating value for natural gas of 1,028 British thermal units (BTU) per SCF and 128,400 BTU per gallon of diesel fuel).

Figure 43: Historical Prices for Natural Gas Used to Make Vehicle Fuel



Source: US Energy Information Administration, 2015

For the baseline scenario, without any biochar added, the estimated RNG production at 300 scfm would be 539,407 diesel gallon equivalents, annually (see Table 21). This would have a value of $469,284 to $674,259. At 74 percent methane after adding biochar, the value of the RNG produced would be $609,008 - $875,011, an increase of $139,724 – $200,752, annually. This represents the gross revenue generated to the project, annually, by adding biochar. The net revenue would account for the operating and maintenance costs as well.

Table 21: Comparison of Biomethane and Tail Gas Production With and Without Biochar Added

Preliminary Financial Analysis			
Assumptions	Base Scenario	Biochar Scenario	
Assumed Methane Concentration of Raw Biogas:	60.0%	74.0%	
BioCNG Fuel Production:	64	84	DGE per Hour
	1,482	1,923	DGE per Day
	10,373	13,462	DGE per Week
	44,951	58,334	DGE per Month
	539,407	700,009	DGE per Year
Waste Gas: *(expected flow to be destructed in a flare, or other device)*	162	121	scfm

Assumptions:
1) Diesel at 128,400 BTU/gal; Gasoline at 111,200 BTU/gal.

Source: CleanWorld

The equipment manufacturer provided detailed estimates for operating and maintenance costs for each scenario. Assuming in both cases the equipment runs for the same length of time, processing biogas where the only difference is in the methane content, the annual O&M costs would be equal. There was no evidence that the biochar changed the hydrogen sulfide content of the biogas (whose change out accounts for 51 percent of the O&M costs). However, because the biochar scenario results in more biomethane output, the cost per diesel gallon equivalent would be reduced by $0.05, which is 4-5 percent of the value of the biomethane (see Table 22).

Table 22: Comparison of Costs for Biogas Cleaning System With and Without Biochar

Maintenance Item	Change Out / Replacement Interval		Baseline (annual)	With Biochar (annual)
Hydrogen Sulfide Media	8 months		$ 64,064	$ 64,064
VOC/Siloxane Media	6 months		$ 21,458	$ 21,458
Oil, CO2 Sensor and Align	1 year		$ 5,500	$ 5,500
Carbon Dioxide Removal	10 years		$ 10,140	$ 10,140
Gas Compressor (refubish)	10 years		$ 1,640	$ 1,640
Modulating Valve (refurbish)	5 years		$ 1,000	$ 1,000
Chiller Compressor (new)	5 years		$ 1,200	$ 1,200
Cost for Substrate	1 month		$ -	$ -
RIN Broker Fee	3 year		$ -	$ -
			$ 105,002	$ 105,002
Labor Type	Hourly Rate			
Labor	$75		$ 15,000	$ 15,000
Management	$150		$ 4,500	$ 4,500
			$ 19,500	$ 19,500
			$ 124,502	**$ 124,502**
Average BioCNG Fuel Production	DGE	per year	539,407	700,009
Average Fueling Station O&M	N/A		$ -	$ -
Average Media O&M Cost per	DGE		$ 0.23	$ 0.18

Notes:
(1) Hydrogen sulfide changeout rate based on 600 ppmv sulfur content at maximum flow rate.
(2) VOC/Siloxane changeout rate based on a VOC/Siloxane cocentration of 2000 ppbv at maximum flow rate.
(3) Oil Change, CO2 Sensor and Laser alignment of Compressor: 4 hours
(4) Labor requirements for changeout of hydrogen sulfide and VOC media: 2 staff members, 12 hours (for each unit)
(5) All piping, tanks, and vessels are assumed to have a 20 year life span.
(6) General operations will require approximately 2 hours of labor per week.
(7) These cost assume work to be performed by owner of equipment without markup that may be required if an outside party purchased the parts or performed the labor.
(8) Verification fees included in Broker fee (annualized cost of verification required every 3 years).
(8) N/A

Source: CleanWorld

Net Economic Benefit of Biochar Addition

Adding biochar to the 100-ton per day digester at the SATS, after the system has reached a stable annual operating capacity equal to its design capacity and predicted yields, will add revenue to the overall project. The total added revenue would be $350,132 to $411,160 per year, depending on the sales price of the biomethane, outlined in Table 23. This analysis assumes that the tail gas would be of sufficient quality to be combusted in the existing 190 kW generator, which would otherwise go unused due to the need for continuous, full-capacity operations. The analysis does not account for any value for Renewable Identification Numbers, Low Carbon Fuel Standard credits, self-generation credits, or other additional incentives for the production of distributed and/or renewable power.

The cost of biochar addition includes the capital costs needed to install equipment that allows for the receiving and metering of biochar to the digester, the additional operating and maintenance costs required for adding the biochar, and the cost of purchasing the biochar.

Capital costs considered for this analysis were the cost of building a storage bunker large enough to hold a week's worth of biochar and a feed auger for metering the biochar into the digester. These costs represent very rough estimates. Nonetheless, the capital costs when amortized over 20 years make up less than 2 percent of the overall costs.

Operating and maintenance costs assumed 3 percent of the capital costs as an annual payment plus labor (at $25 per hour) and operating costs for the front-end loader at $100 per day. These are rough estimates as well, but they made up only 5 percent of the overall costs. Over 90 percent of the overall costs were due to the purchase price of biochar itself.

The lowest available price online (for foreign, bulk shipments, as advertised) currently is about $200 per ton. This is 80 percent less than the cost actually paid during this study. At the required loading rate, even this low cost was more than twice as much as the additional revenue generated. In order for the project to be cost neutral, biochar would have to cost $65 to $80 per ton, less than half of the lowest currently available price.

Table 23: Cost Summary for Adding Biochar to a 100 Ton per Day Digester

	Cost Elements	Value	Units
Basic Biochar Information			
	Biochar Loading Rate	12	tons per day
		84	tons per week
		4,380	tons per year
	Bulk Density of Biochar	5.6	lbs/cu ft
	Storage Volume Needed for One Week's Supply	1,111	cubic yards
		224,416	gallons
	Storage Bunker Dimensions	60' x 60' x 10'	
Capital Costs for Biochar Loading Equipment			
	Storage Bunker	$200,000	
	Feed Auger	$30,000	
	Additional Balance of Plant	$50,000	
	Total Capital Costs	*$280,000*	
	Total Capital Costs, Ammortized over 20 years	*$14,000*	*per year*
Operating and Maintenance Costs for Biochar Loading Equipment			
	O&M on bunker and feed auger	$8,400	per year
	Front end loader operation	$26,000	per year
	Labor (10 man hours per week)	$13,000	per year
	Total Operating and Maintenance Costs	*$47,400*	*per year*
Cost of Purchasing Biochar			
	Biochar at $200 per ton	$876,000	per year
	Biochar at $400 per ton	$1,752,000	per year
	Biochar at $1,000 per ton	$4,380,000	per year
Revenues from Biochar Addition			
	Added Electricity Revenue	$210,408	per year
	Added RNG Revenue - low	$139,724	per year, minimum
	Added RNG Revenue - high	$200,752	per year, maximum
	Total Gross Revenues - low	$350,132	per year, minimum

	Cost Elements	Value	Units
	Total Gross Revenues - high	$411,160	per year, maximum
Summary			
	Total Capital and O&M Costs, before additional cost of biochar	$61,400	per year
	Total Costs at Lowest Current Price of Biochar	$937,400	per year
	Additional Cost Tolerance for Net Zero Revenue	$288,732	per year, minimum
		$349,760	per year, maximum
	Tolerable Cost of Biochar	$65.92	per ton, minimum
		$79.85	per ton, maximum

Source: CleanWorld

Based on the above analysis, biochar addition to AD is not currently a cost effective additive process. The most effective method for improving the economics of biochar addition would be to focus on reducing the cost of biochar addition. Market forces will determine the value of biochar in the future. One economic study suggested that as demand for biochar in the agricultural sector grows, biochar prices could fall as low as $100 per ton. Supply side forces could also drive down prices of biochar. Foreign sources could flood the market causing biochar prices to fall. If these forces reduce the price to less than $80 per ton, it may be advisable to revisit the use of biochar as an additive.

Another way to reduce the cost of biochar addition would be to reduce the required loading rate. Since the effect of biochar is primarily physical and the biochar itself is not consumed, then it may be possible to recycle a fraction of the available biochar. The key would be to recycle and therefore retain more biochar without building up other solids or chemicals that could adversely affect the digester health. Further research is needed to determine the best way to recycle biochar and to prove that doing so would be beneficial to digester operations. There are some indications that biochar may be accumulating in the digester already. This could be due to the anaerobic sequencing batch design of the digester which retains particulates that tend to sink or float in the reactor. In the economic analysis, the tolerable cost of biochar was calculated by dividing the cost tolerance for net zero revenue by the annual biochar loading rate. Therefore, reducing the loading rate by 90 percent would increase the tolerable cost of biochar by 10x. Clearly, this would make the process more financially feasible.

If the biochar does wash through and end up in the solid digestate removed, the biochar could potentially enhance the value of the digestate as an agricultural amendment (Woolf et al., 2010).[22] The moisture absorption and cationic content of the biochar can improve soil quality. A 100 ton per day digester system should produce 10 – 15 tons of digestate (neglecting any additional mass change during maturation). This is roughly equal to the biochar loading rate.

Assuming half of the biochar could be recovered at 50 percent moisture content along with the rest of the digestate, the quantity of digestate recovered should be approximately double the amount of biochar loaded. Thus, for each dollar of increased value of a ton of digestate, the cost of a ton of biochar would decrease effectively by $2.00.

For example, bulk compost typically sells for $20 - $40 per ton. If adding biochar doubled the value of the compost, the cost of the biochar would effectively be decreased by $40 - $80 per ton. The cost of biochar has to be reduced by $150 - $950 per ton, according to the economic analysis. The true value of biochar as an agricultural amendment needs to be better understood, especially as blended with digester solids.

Another way to look at it would be from the opposite vantage point. Adding digester solids to biochar should not decrease the value of the biochar. Then the biochar would be cost neutral and the additional revenue generated by improving biogas quality would justify the capital outlay and operating costs. This would be a good target for future research which could determine the agronomic benefits of blending digester solids with biochar and the market potential of a blended product.

Quantitative Performance and Cost Objectives at ARP Field Demonstration

The following were the objectives set out at the beginning of the project:

- Divert 10 tons per day of wet waste feedstock from area landfills in Sacramento to single digester
- Provide renewable energy supply of over 50,000 scf of CNG per day and displace over 500 gallons of gasoline per day
- Co-produce over 2,000 kWh per day of electricity at field demonstration (for parasitic use)
- Ultimate target cost for added biomethane production is less than $5 to $7 per Million British Thermal Units (BTU)

While the CleanWorld digester facility at ARP was originally designed to receive up to 10 tons per day of feedstock, it was decided for the purposes of this study that the ARP digester facility should not be run at its maximum capacity to ensure that the digester could run smoothly without interruption to give the additive the best chance to succeed. Therefore, the digester was loaded with a single 6,000 gallon tanker truck load once per week, which is equivalent to loading 25 tons per week, or 3.5 tons per day. Originally, feedstocks were sought that could be loaded directly at ARP, but no suitable feedstocks were discovered during the resource assessment phase of the project. Therefore, it was decided that pre-processed feedstock from one of CleanWorld's other commercial AD facilities would be used as the feed for this study. This provided additional space at the other facilities for diverting more waste from area landfills.

CleanWorld's other digester facilities that provided the feedstock produce both CNG and electricity from biogas. The ARP digester where the study took place did not produce enough biogas during the course of the study to sustain the microturbines. Therefore, the biogas was flared as per the air permit. The ARP digester produced up to 74,000 scf of biogas at 67.3 percent methane per week, or 49,800 scf of methane. Since the digester was run at about 10 percent of its designed capacity, even with 30 percent methane loss during conversion to CNG, at full capacity the digester should be capable of producing 50,000 scf of CNG. Currently, CleanWorld's facility routinely produces over 180,000 scf of biogas at 58 percent methane, which would generate 73,000 scf of CNG.

The field demonstration facility has two 65 kW mictroturbines with heat recovery, giving the facility a nameplate capacity of up to 135 kW of electricity. The goal to produce 2,000 kWh per day would require running 83.33 kW of the microturbine capacity 24 hours per day. As mentioned, these turbines were not utilized during the field demonstration. One of the facilities that provided the feedstock also has a microturbine. That facility routinely produces over 200 kWh per ton of feedstock loaded. Therefore, the design capacity of 10 tons per day should produce over 2,000 kWh. The 3.5 tons per day loaded during this study allowed the facility to produce over 700 kWh per day of electricity.

According to the economic analysis, the added cost of the biochar loading system was $61,400 per year without including the cost of the biochar. This was estimated to boost biomethane production by 20,621 mmBTU per year. This would give the added biomethane a cost of $2.98 per mmBTU. Adding the cost of biochar at the lowest available current price ($200 per ton) increases the biomethane cost to $45.49 per mmBTU. At the minimum cost for biochar that allows the project to break even, the biomethane then would cost $14.00 per mmBTU. To keep the cost of biomethane below $7 per mmBTU, biochar would have to add less than $82,947 per year to the overall annual expenses. At the current loading rate, that would equate to $18.94 per ton of biochar.

GLOSSARY

AMERICAN RIVER PACKAGING (ARP) - A privately held packaging company founded in 1980, specializing in corrugated packaging, custom foam inserts, and point of purchase solutions.[41]

AMMONIA (NH3) -- A pungent colorless gaseous compound of nitrogen and hydrogen that is very soluble in water and can easily be condensed into a liquid by cold and pressure. Ammonia reacts with NOx to form ammonium nitrate -- a major PM2.5 component in the western United States.

ANAEROBIC DIGESTION (AD) -- A biological process in which biodegradable organic matters are broken down by bacteria into biogas, which consists of methane (CH4), carbon dioxide (CO2), and other trace amount of gases. The biogas can be used to generate heat and electricity.

ARGONNE NATIONAL LABORATORY (ANL or Argonne) - The first and the largest of the national labs chartered in 1946 in DuPage County, Illinois. The US Department of Energy funds Argonne National Lab and University of Chicago Argonne, LLC manages the site. Argonne National Lab is the descendant of Chicago's Metallurgical Laboratory and the home of Enrico Fermi's first controlled nuclear chain reaction demonstration. Today the Argonne Laboratory consists of the Argonne Advanced Photon Source, The Argonne Tandem Linear Accelerator System and conducts basic scientific research, conducts experiments on clean energy sources, manages environmental problems nationally, and most importantly reviews and monitors national security risks.[42]

BIOCHAR - a solid material obtained from the carbonization thermochemical conversion of biomass in an oxygen-limited environments. In more technical terms, biochar is produced by thermal decomposition of organic material (biomass such as wood, manure or leaves) under limited supply of oxygen (O_2), and at relatively low temperatures (<700°C). This process mirrors the production of charcoal, which is perhaps the most ancient industrial technology developed by humankind. Biochar can be distinguished from charcoal—used mainly as a fuel—in that a primary application is use as a soil amendment with the intention to improve soil functions and to reduce emissions from biomass that would otherwise naturally degrade to GHGs.[43]

BIOGAS -- The mixture of methane, carbon dioxide, and other minor gases formed from the decomposition of organic materials.

---

41 ARP Linkedin webpage: https://www.linkedin.com/company/american-river-packaging?trk=similar-pages_result-card_full-click

42 PhysOrg: Argonne National Laboratory. https://phys.org/partners/argonne-national-laboratory/

43 International Biochar Initiative Website: https://biochar-international.org/biochar/

BIOLOGICAL OXYGEN DEMAND (BOD) - the amount of dissolved oxygen needed (i.e. demanded) by aerobic biological organisms to break down organic material present in a given water sample at certain temperature over a specific time period.

BRITISH THERMAL UNIT (BTU) - The standard measure of heat energy. It takes one Btu to raise the temperature of one pound of water by one degree Fahrenheit at sea level. For example, it takes about 2,000 Btu to make a pot of coffee. One Btu is equivalent to 252 calories, 778 foot-pounds, 1055 joules, and 0.293 watt-hours.

CALIFORNIA ENERGY COMMISSION (CEC) - The state agency established by the Warren-Alquist State Energy Resources Conservation and Development Act in 1974 (Public Resources Code, Sections 25000 et seq.) responsible for energy policy. The Energy Commission's five major areas of responsibilities are:

- Forecasting future statewide energy needs
- Licensing power plants sufficient to meet those needs
- Promoting energy conservation and efficiency measures
- Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels
- Planning for and directing state response to energy emergencies.

CARBON DIOXIDE (CO_2) – A colorless, odorless, nonpoisonous gas that is a normal part of the air. Carbon dioxide is exhaled by humans and animals and is absorbed by green growing things and by the sea. CO_2 is the greenhouse gas whose concentration is being most affected directly by human activities. CO_2 also serves as the reference to compare all other greenhouse gases (see carbon dioxide equivalent).

CHEMICAL OXYGEN DEMAND (COD) – A measure of the oxygen-consuming capacity of organic matter present in wastewater. Chemical oxygen demand is expressed as the amount of oxygen consumed from a chemical oxidant in mg/L during a specific test.[44]

CLEAN CITIES PROGRAM – As part of the U.S. Department of Energy's Vehicle Technologies Office, Clean Cities coalitions foster the nation's economic, environmental, and energy security by working locally to advance affordable, domestic transportation fuels, energy efficient mobility systems, and other fuel-saving technologies and practices. Since beginning in 1993, Clean Cities coalitions have achieved a cumulative impact in energy use equal to nearly 8 billion gasoline gallon equivalents through the implementation of diverse transportation projects.[45]

---

44 California State University, Sacramento, Department of Civil Engineering Water Program, online glossary: http://www.owp.csus.edu/glossary/cod.php

45 U.S. Department of Energy, Energy Efficiency and Renewable Energy, Clean Cities (https://cleancities.energy.gov/about/)

COARSE WALNUT BIOCHAR (CW) – A walnut biochar with a larger particle size, approximately 24 wt percent below a particle size of 500 μm.

COMPRESSED NATURAL GAS (CNG) - Natural gas that has been compressed under high pressure, typically between 2,000 and 3,600 pounds per square inch, held in a container. The gas expands when released for use as a fuel.

DEIONIZED - Deionization means the removal of ions from water. Ions are electrically charged atoms or molecules found in water that have either a net negative or positive charge. For many applications that use water as a rinse or ingredient, these ions are considered impurities and must be removed from the water.[46]

FATS, OIL AND GREASE (FOG) - a combination of fats, oils, and grease used in food processing and the preparation of meals. FOG bearing materials include Cooking oil, Fat, Lard, Grease, Butter, Tallow, Shortening, Margarine, Meat, Sauces, Cookies and pastries. Waste FOG accumulates in the sewer system causing obstruction or blockage of the sewer pipe, ultimately resulting in a sewer overflow. FOG also accumulates in pump station wet wells and primary settling tanks causing a decrease in capacities and an increase maintenance requirements.[47]

FINE WALNUT BIOCHAR (FW) – A walnut biochar with a smaller particle size, approximately 77 wt percent below a particle size 500 μm.

GREEN RESTAURANTS ALLIANCE SACRAMENTO (GRAS) - Dedicated to growing a sustainable food community in California's Farm-to-Fork Capital. Our mission is to educate and inspire Sacramento to "care" for its waste stream, using it as a resource to build organic gardens and green, climate resilient landscapes in every Sacramento neighborhood. GRAS is working with the Cal EPA - Air Resources Board, Cal Recycle, and the County of Sacramento - Solid Waste Authority, and Californians Against Waste to ensure that community composting can be fully permitted in Sacramento and throughout the State.[48]

GREENHOUSE GAS (GHG) - Any gas that absorbs infra-red radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halogenated fluorocarbons (HCFCs), ozone (O_3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs). (EPA)

---

46 Puretech Industrial Water Website: https://puretecwater.com/deionized-water/what-is-deionized-water

47 City of Los Angeles, LA Sanitation, "Fats, Oils and Grease Control." LA Sanitation webpage for FOGs: https://www.lacitysan.org/san/faces/home/portal/s-lsh-wwd/s-lsh-wwd-cw/s-lsh-wwd-cw-iwm/s-lsh-wwd-cw-iwm-pp/s-lsh-wwd-cw-iwm-fog;jsessionid=1CUYwXdkm6LQGcsvzTkI_xEiSWBosfTxB4QteGJ8pllWEUxHCRus!-157072356!-497666524?_afrLoop=13448327570408771&_afrWindowMode=0&_afrWindowId=null&_adf.ctrl-state=16jdk2m7d7_1#!%40%40%3F_afrWindowId%3Dnull%26_afrLoop%3D13448327570408771%26_afrWindowMode%3D0%26_adf.ctrl-state%3D16jdk2m7d7_5

48 Green Restaurants Alliance Website: http://www.grasacramento.org/

HYDRAULIC RETENTION TIME (HRT) - a measure of the average length of time that a soluable compound remains in a constructed bioreactor. The volume of the aeration tank divided by the influent flowrate is T (tau), the hydraulic retention time.[49]

HYDROGEN SULFIDE (H2S) – A highly flammable, explosive gas. H2S burns and produces other toxic vapors and gases, such as sulfur dioxide.

LITER (L) – A metric unit of capacity equal to one cubic decimeter.

METHANE (CH4) - A light hydrocarbon that is the main component of natural gas and marsh gas. It is the product of the anaerobic decomposition of organic matter, enteric fermentation in animals and is one of the greenhouse gases. Chemical formula is CH4.

MMBtu - 1 million Btu.

MUNICIPAL SOLID WASTE - Locally collected garbage, which can be processed and burned to produce energy.

NITROGEN (N, N2) – An essential element of life and a part of all plant and animal proteins. Nitrogen is commercially recovered from the air as ammonia, which is produced by combining nitrogen in the atmosphere with hydrogen from natural gas.[50]

ORGANIC LOADING RATE (OLR) - Defined as the application of soluble and particulate organic matter. It is typically expressed on an area basis as pounds of BOD5 per unit area per unit time, such as pounds of BOD5 per square foot per day (lb/ft2 /day).[51]

PACIFIC GAS AND ELECTRIC COMPANY (PG&E) – An electric and natural gas utility serving the central and northern California region.

PARTS PER MILLION (PPM) – Concentrations in soil or water can be expressed in PPM. For soil, one PPM = one mg/kg of contaminant. For water, one PPM = approximately 1 mg/L of contaminant.[52]

POSITIVE CONTROL (PC) - A positive control group is a control group that is not exposed to the experimental treatment but that is exposed to some other treatment that is known to produce the expected effect. These sorts of controls are particularly useful for validating the experimental procedure.[53]

---

49 Lenntech Webiste: https://www.lenntech.com/wwtp/hrt.html

50 U.S. Geological Survey: https://www.usgs.gov/
51 Washington State Department of Health, Wastewater Management Program, Rule Development Committee, Draft Issue Research Report, Organic Loading Rates. April 2002. Department of Health Draft Issue Research Report PDF: https://www.doh.wa.gov/portals/1/Documents/Pubs/337-102.pdf

52 Kansas State University (https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.files/fileID/14285)
53 Understanding Science, University of California at Berkeley https://undsci.berkeley.edu/faqs.php

POUNDS PER SQUARE INCH (PSI) – A unit of pressure or stress based on avoirdupois units. It is the pressure resulting from a force of one pound-force applied to an area of one square inch.

POUNDS PER SQUARE INCH GAUGE (PSIG) – The pressure relative to atmosphere.

RENEWABLE FUEL STANDARD - A federal program to increase the volume of renewable fuels used in transportation fuels. Created under the Energy Policy Act of 2005, and revised by the Energy Independence and Security Act of 2007, the RFS program requires increasing annual volumes of renewable fuel, starting from 9 billion gallons in 2008 to 36 billion gallons by 2022. Within those total volumes, the RFS also requires certain volumes of specific fuels, such as cellulosic and advanced biofuels.

RENEWABLE NATURAL GAS (RNG) **-** A gaseous mixture of carbon dioxide and methane produced by the anaerobic digestion of organic matter.

SACRAMENTO INTERNATIONAL AIRPORT (SMF) – An airport 10 miles (16 km) northwest of downtown Sacramento, also known as the Capital City for the state, in Sacramento County, California. It serves the Greater Sacramento Area, and it is run by the Sacramento County Airport System.

SACRAMENTO MUNICIPAL UTILITY DISTRICT (SMUD) - An electric utility serving the greater Sacramento, California, region.

SACRAMENTO SOLID WASTE AUTHORITY (SWA) - Formed in 1992, the Sacramento Regional Solid Waste Authority (SWA) is a joint powers authority that oversees commercial waste management in the City of Sacramento and the unincorporated areas of Sacramento County.[54]

SOUTH AREA TRANSFER STATION (SATS) – an Organic Waste Recycling Center, in Sacramento, CA.

STANDARD CUBIC FEET PER MINUTE (SCFM) -- The molar flow rate of a gas corrected to standardized conditions of temperature and pressure thus representing a fixed number of moles of gas regardless of composition and actual flow conditions.

STANDARD CUBIC FOOT (SCF) – One cubic foot of gas at standard temperature and pressure (60˚F [15.6˚C] at sea level). Since both temperature and air pressure affect the energy content of a cubic foot of natural gas, the SCF is a way of standardizing. One SCF = 1,020 BTUs.

TOTAL DISSOLVED SOLIDS (TDS) – Inorganic and organic substances contained in water that can pass through a 2 micron filter.

---

54 Sacramento Regional Solid Waste Authority, Website Homepage, https://swa.saccounty.net/Pages/default.aspx

TOTAL KJELDAHL NITROGEN (TKN) - The sum of nitrogen bound in organic substances, nitrogen in ammonia (NH3-N) and in ammonium (NH4+-N) in the chemical analysis of soil, water, or waste water (e.g. sewage treatment plant effluent).

TOTAL SUSPENDED SOLIDS (TSS) - The dry weight of suspended particles that are not dissolved in a sample of water that can be trapped by a filter that is analyzed using a filtration apparatus. It is a water quality parameter used to assess the quality of a specimen of any type of water or water body, ocean water for example, or wastewater after treatment in a wastewater treatment plant.

TOTAL ORGANIC CARBON (TOC) - Total gaseous organic compounds (minus methane and ethane) in a vent stream, with the concentrations expressed on a carbon basis. [40 CFR 63.1101 (CFR 2013)]. (U.S. EPA)

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (U.S. EPA) -- A federal agency created in 1970 to permit coordinated governmental action for protection of the environment by systematic abatement and control of pollution through integration or research, monitoring, standards setting and enforcement activities.

UNIVERSITY OF CALIFORNIA, DAVIS (U.C. Davis) – A public research university located in Davis, California. It is one of the 10 campuses in the University of California (UC) system.

VOLATILE SOLIDS (VS) - Those solids in water or other liquids that are lost on ignition of the dry solids at 550° centigrade.[55]

WASTEWATER TREATMENT PLANT (WWTP) - A facility that receives wastewaters (and sometimes runoff) from domestic and/or industrial sources, and by a combination of physical, chemical, and biological processes reduces (treats) the wastewaters to less harmful byproducts; known by the acronyms, STP (sewage treatment plant), and POTW (publicly owned treatment works). (U.S. EPA)

55 EPA Glossary Website: https://ofmpub.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do?details=&vocabName=Terms%20of%20Env%20(2009)&filterTerm=volatile%20solid&checkedAcronym=true&checkedTerm=true&hasDefinitions=false&filterTerm=volatile%20solid&filterMatchCriteria=Contains

REFERENCES

Beil, M., Beyrich, W., Holzhammer, U., Krause, T. 2013. Biomethane, Agency for Renewable Resources. Gulzow-Pruzen, Germany.

Brewer, C.E., Schmidt-Rohr, K., Satrio, J.A., Brown, R.C. 2009. Characterization of biochar from fast pyrolysis and gasification systems. *Environmental Progress & Sustainable Energy*, **28**(3), 386-396.

Brown, R.C. 2011. Thermochemical processing of biomass: Conversion into fuels, chemicals and power. in: *Wiley Series in Renewable Resource*, (Ed.) C. Stevens, Wiley. Great Britain.

California Energy Commission. 2014. *Overview of Natural Gas in California.* CEC Energy Almanac. CEC webpage about natural gas: https://ww2.energy.ca.gov/almanac/naturalgas_data/overview.html

Chen, Y., Cheng, J.J., Creamer, K.S. 2008. Inhibition of anaerobic digestion process: A review. *Bioresource Technology*, **99**(10), 4044-4064.

De la Rubia, M.A., Riau, V., Raposo, F., Borja, R. 2013. Thermophilic anaerobic digestion of sewage sludge: focus on the influence of the start-up. A review. *Crit Rev Biotechnol*, **33**(4), 448-60.

EPA. 2012. Municipal Solid Waste.

Grimberg, S.J., Hilderbrandt, D., Kinnunen, M., Rogers, S. 2015. Anaerobic digestion of food waste through the operation of a mesophilic two-phase pilot scale digester - Assessment of variable loadings on system performance. *Bioresource Technology*, **178**, 226-229.

Innovation Center for US Dairy. 2013. National Market Value of Anaerobic Digestion Products. Prepared by Informa Economics.

International Biochar Initiative. 2013. State of the Biochar Industry, International Biochar Initiative State of Industry webpage: https://biochar-international.org/state-of-the-biochar-industry-2013/. (accessed December 5, 2019).

Keiluweit, M., Nico, P.S., Johnson, M.G., Kleber, M. 2010. Dynamic molecular structure of plant biomass-derived black carbon (biochar). *Environ Sci Technol*, **44**(4), 1247-1253.

Laird, D. 2014. Pathways to Carbon Negative Energy. Article PDF: https://www.biorenew.iastate.edu/files/2014/06/lairdd.pdf.

Levin, J., Mitchell, K., Swisher, H. 2014. Decarbonizing the Gas Sector: Why California Needs a Renewable Gas Standard, Bioenergy Association of California.

Lombardi, L., Carnevale, E. 2013. Economic evaluations of an innovative biogas upgrading method with CO2 storage. *Energy*, **62**, 88-94.

Metcalf, Eddy. 2003. *Wastewater Engineering: Treatment and Reuse*. *4th ed*. McGraw-Hill, Boston.

Murray, B., Galik, C., Vegh, T. 2014. Biogas in the United States: An Assessment of Market Potential in a Carbon-Constrained Future, Nicholas Institute for Environmental Policy Solutions. Duke University.

Pan, S.-Y., E., C.E., Chiang, P.-C. 2012. CO_2 capture by accelerated carbonation of alkaline wastes: A review on its principles and applications. *Aerosol and Air Quality Research*, **12**(5), 770-791.

RE, S. 1996. Anaerobic Biotechnology for Industrial Wastewater, Archae Press. Nashville, TN.

Sanna, A., Uibu, M., Caramanna, G., Kuusik, R., Maroto-Valer, M.M. 2014. A review of mineral carbonation technologies to sequester CO_2. *Chem Soc Rev*, **43**(23), 8049-80.

Shen, Y., Linville, J.L., Urgun-Demirtas, M., Mintz, M.M., Snyder, S.W. 2015a. An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: challenges and opportunities towards energy-neutral WWTPs. *Renewable & Sustainable Energy Reviews*, **50**, 346–362.

Shen Y, Linville JL, Urgun-Demirtas M, Schoene RP, Snyder SW. 2015b. Producing pipeline-quality biomethane via anaerobic digestion of sludge amended with corn stover biochar with in-situ CO2 removal, *Applied Energy*, **158**, 300-309.

Snyder, S.W., Urgun-Demirtas, M., Shen, Y. 2014. Method for generating methane from a carbonaceous feedstock, U.S. Patent Serial No. 14/540,393. Argonne National Laboratory. USA.

Suryawanshi, P.C., Chaudhari, A.B., Kothari, R.M. 2010. Thermophilic anaerobic digestion: the best option for waste treatment. *Crit Rev Biotechnol*, **30**(1), 31-40.

USEPA. 2010. Clean Watersheds Needs Survey 2008 - Report to Congress. US Environmental Protection Agency. EPA-832-R-10-002.

USEPA. 2011. Opportunities for combined heat and power at wastewater treatment facilities: Market analysis and lessons from the field. United States Environmental Protection Agency.

USEPA. 2014a. RFS Renewable Identification Number (RIN) Quality Assurance Program; Final Rule. in: *40 CFR Part 80*, Vol. 79, United States Environmental Protection Agency. Washington, DC.

USEPA. 2014b. EPA webpage for water topics:
http://water.epa.gov/type/watersheds/trading/finalpolicy2003.cfm
http://water.epa.gov/type/watersheds/trading/upload/wri-mrb-trading-report.pdf. (accessed February, 10, 2015).

Vlyssides, A., Karlis, P.K. 2004. Thermal-alkaline solubilization of waste activated sludge as a pre-treatment stage for anaerobic digestion. *Bioresource Technology*, **91**(2), 201-206.

WEF. 2013. Biogas Production and Use at Water Resource Recovery Facilities in the United States. Water Environment Federation.

WERF. 2008. State of Science Report: Energy and Resource Recovery from Sludge. Water Environment Research Foundation.

Whitfield, J. 2013. Getting the Biochar Industry Up to Speed: What Can We Learn From the Pellet Business?, Article from International Biochar Initiative Website: https://biochar-international.org/getting-the-biochar-industry-up-to-speed-what-can-we-learn-from-the-pellet-business/ (accessed December 5, 2019).

Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S. 2010. Sustainable biochar to mitigate global climate change. *Nat Commun*.,1, 56, 1-9.

Yang, Y., Yu, K., Xia, Y., Lau, F.T.K., Tang, D.T.W., Fung, W.C., Fang, H.H.P., Zhang, T. 2014. Metagenomic analysis of sludge from full-scale anaerobic digesters operated in municipal wastewater treatment plants. *Applied Microbiology and Biotechnology*, **98**(12), 5709-5718.

Zhang, C.S., Su, H.J., Tan, T.W. 2013. Batch and semi-continuous anaerobic digestion of food waste in a dual solid-liquid system. *Bioresource Technology*, **145**, 10-16.

Zhang, L., Jahng, D. 2012. Long-term anaerobic digestion of food waste stabilized by trace elements. *Waste Management*, **32**(8), 1509-1515.