Anaerobic Codigestion of Food Waste to Increase Methane Yields

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Up to 63 mil tons of food waste are produced in the United States each year ("USEPA Food Recovery Hierarchy," 2016). Food waste significantly contributes to landfill methane emissions and high concentrations of chemical oxygen demand (COD) and ammonia in leachate (Trabold and Nair, 2018). Characteristics of food waste also pose challenges to other solid waste management options; for example, food waste is a poor incineration feedstock due to its high moisture content and low calorific value (Lee et al., 2020).

Different states also have different policies in regard to organic waste. Florida previously enacted but fell short of the 75 percent recycling goal for 2020 and may require creative solutions to help reach future thresholds (Florida Senate and House of Representatives, 2019).

A more-desirable option for treating food waste is through anaerobic digestion, which diverts the waste from landfills and incinerators, while producing biogas (a mixture of methane and carbon dioxide) and fertilizer as valuable byproducts (Hinds et al., 2017). Management of food waste through anaerobic codigestion is a well-established technology in Europe and has had an increase in popularity in the U.S. (Baere and Mattheeuws, 2015).

A common attribute of these systems, however, is that they only accept preconsumer waste, such as the waste seen in Figure 1, due to the risk of contamination of postconsumer food waste with nonbiodegradable components, such as single-use plastic tableware and containers (Zhu et al., 2010). Between 15 and 30 percent of postconsumer food is wasted, and 97 percent of this food waste ends up in landfills, which is the least desirable method for food-waste disposal (Trabold and Nair, 2018; "USEPA Food Recovery Hierarchy," 2016).

Figure 1. An example of preconsumer waste from college dining halls.

In addition, food waste is often not a desirable anaerobic digestion (AD) substrate on its own due to its low carbon-to-nitrogen (C/N) ratio, resulting in a high concentrations of volatile fatty acids (VFA) and free ammonia nitrogen (FAN) in the digester that inhibit methanogenesis (Dixon et al., 2019). Prior studies have shown that codigestion of food waste with high C/N feedstocks, such as yard waste and sewage sludge, results in increased methane yields compared with AD of food waste alone (Lee et al., 2019).

Background

This study grew out of a partnership between the University of South Florida (USF) and TBD Café, a tea wholesaler in Riverview, Fla., which is near Tampa, seeking to form a partnership to divert postconsumer waste from incineration, improve biomethane production from food waste, and prevent contamination of the waste from cafeterias and restaurants normally caused by single-use plastics. The overall goal was to evaluate the effects of AD of food waste, with sugarcane-bagasse (SCB) compostable plates and/or tea leaves at varying mixing ratios.

The SCB is a lignocellulosic-rich waste product of sugar and bioethanol production (Mustafa et al., 2018). For every ton of sugarcane used, between 250 and 280 kg of SCB is produced (Vats et al., 2019). Florida has over 440,000 acres of farmland dedicated to sugarcane growth (Baucum and Rice, 2009). The SCB can be molded into compostable tableware, minimizing bagasse waste and offsetting the use of single-use plastics (Loh et al., 2013).

Prior studies have investigated AD of SCB after pretreatment to allow anaerobic microbes to penetrate the cell wall (Zheng et al., 2014). Vats et al. (2019) codigested acid-treated SCB with food waste at varying ratios. A 1:1 ratio of SCB to food waste resulted in the highest biogas yield of 1,404 ml biogas/g volatile solids (VS) added. Mustafa et al. (2018) reported a maximum methane yield of 220 ml CH_4/g VS with alkaline pretreated at 180°C.

The authors recommend a combination of heat and chemical pretreatment to maximize methane yield. Nosratpour et al. (2018) observed a maximum methane yield of 239 ml CH_4/g VS with alkaline-pretreated SCB; however, little information is available about anaerobic codigestion of food waste with SCB-based compostable tableware.

The world tea industry is valued at $55 billion; an estimated 30 to 36 bil liters of tea are consumed annually, representing a large volume of tea-leave waste product (Kumar and Deshmukh, 2020). Florida is also looking to tap into the growth of the tea market with tea wholesalers, as well as research the growing market (UF IFAS, n.d.); however, little is known about AD of tea leaves. Goel et al. (2001) investigated AD of tea leaves and did not observe significant methane production without nutrient

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Table 1. Biochemical Methane Potential Assay Compositions During Different Experimental Phases

Phase	Substrates	Mixing Ratio[a]	Inoculum
Phase 1	FW	n/a	Unacclimated
	FW+TL	1:1	Unacclimated
	FW+CP	1:1	Unacclimated
Phase 2	FW+TL+CP	2:1:1	Acclimated
	FW+TL+CP	1:1:1	Acclimated

a. Food waste (FW), tea leaves (TL), compostable plates (CP)
b. Mixing ratio = FW total solids (TS): codigestion substrate TS

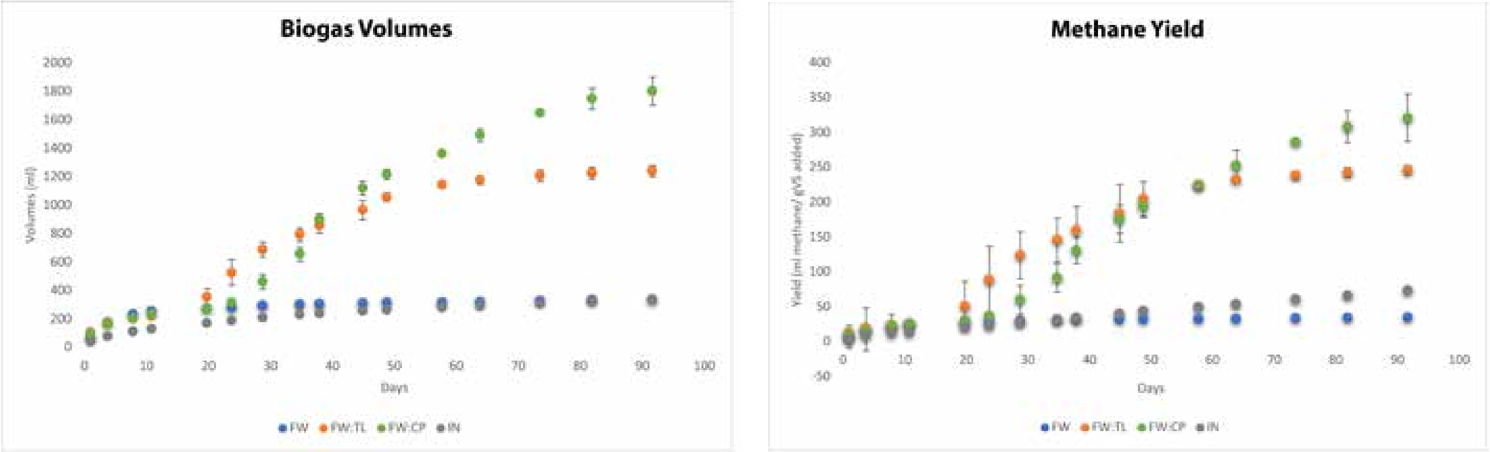

Figure 2. a) Cumulative biogas volume and b) methane yields (normalized to g/volatile solids added) for Phase 1 biochemical methane potential assays.

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addition. After nutrients were added, the authors achieved a methane yield of 146 ml CH_4/g VS.

Materials and Methods

Biochemical methane potential (BMP) assays were set up in the environmental engineering laboratories at USF with varying substrates, codigestion mixing ratios, and inoculum sources (Table 1).

Table 2: Final Chemical Analysis Results for Phase 1 Biochemical Methane Potential Assays

Digestion Set	VS Reduction (%)	Final pH	Ammonia (mg/L)	VFA:Alk Ratio	Methane Quality (%)	CH_4 Yield (ml CH_4/g VS)
Inoculum	54.8±0.2	8.96±0.02	864±174	0.015±0.009	51±27	73±0.0
FW	40.7±0.1	5.06±0.07	862±33	2.12±0.10	39±8	35±4.9
FW+TL	62.4±3.0	8.99±0.03	371±14	0.017±0.001	63±15	246±6.7
FW+CP	60.6±2.5	8.91±0.04	523±14	0.035±0.003	57±15	322±34.1

Materials

The food waste was collected from the dining services at USF and processed in an InSinkErator Inc. (Mount Pleasant, Wis.) 350-horsepower garbage disposal. The waste composition varied in different phases due to the differences in waste produced by dining halls. Spent tea leaves were provided by TBD Café and used as received. The tea leaves were a mixture of green, black, and oolong teas, and included flavor additives, such as ginger. The SCB-based molded compostable plates were purchased from Monogram Cleaning Disposables Inc. (Rosemont, Ill.) and cut into ~ 1cm-sized strips using scissors.

Phase 1 inoculum consisted of effluent from a mesophilic AD at a wastewater treatment facility in Clearwater. In order to reduce the lag period, Phase 2 inoculum consisted of 75 percent Clearwater AD effluent and 25 percent digestate from Phase 1 BMPs (referred to as "acclimated" inoculum in Table 1).

Biochemical Methane Potential Assays

The BMPs are described in detail in Panesar (2020). Briefly, BMPs were set up in 250-mL septum-sealed glass serum bottles at a TS content of 2.5 percent and a food-to-microorganisms (F/M) ratio of 1 based on VS BMPs was incubated in a constant temperature room under mesophilic (35ºC) conditions. Each digestion set included three sets of duplicates; inoculum-only controls were also set up in duplicate. Duplicate BMPs were sacrificed for chemical analysis on weeks 1 and 3 and at the end of the assay.

Analytical Methods

Standard Methods (APHA, 2018) was used to measure methane content (6211-C), TS, VS (2540), soluble COD (sCOD; 5200), VFA (5560-D) and alkalinity (Alk:2320-B). Biogas volume was measured using a frictionless glass syringe. Ammonia concentrations were measured using a Timberline (Boulder, Colo.) TL-2800 Ammonia Analyzer. Samples for COD, VFA, pH, alkaline, and ammonia were first centrifuged at 9800 revolutions per minute (rpm) for 20 minutes, and then filtered through a 0.45 µm glass filter prior to testing. Statistical analysis was done using a two-tailed t-test with a 95 percent confidence interval. Analysis of the covariance (ANCOVA) with a 95 percent confidence interval was also done on the methane yields over time to see if there was a difference in the methane yields of the BMPs.

Results and Discussion

Anaerobic Digestion of Food Waste Alone and Codigestion with Tea Leaves or Compostable Plates

During Phase 1 a comparison was made of AD with food waste alone and with codigestion of food waste with either tea leaves or compostable plates at a 1:1 mixing ratio over a 92-day period (Figure 2 and Table 2). Digesters with food waste alone achieved a 40 percent VS reduction, but a very low methane yield (35 mL CH_4/g VS), which was lower than inoculum-only controls (73 mL CH_4/g VS). The low final pH and VFA:Alk (Table 2) indicate that the rate of fermentation exceeded the rate of methanogenesis, resulting in almost complete inhibition of methanogenic activity.

In contrast with food waste alone, significantly higher methane yields were achieved for food waste and tea leaves (246 mL CH_4/gVS) and food waste and compostable plates (322 mL CH_4/g VS). The food waste and tea leaves had a slightly higher, but not significantly different, methane quality than food waste and compostable plates (Table 2). The large standard deviations in methane quality can be attributed to the slow growth rate of the methanogens at the beginning of digestion (2017).

Both Phase 1 codigestion sets achieved similar VS reduction (Table 1). The tea leave or compostable plate addition brought the pH, VFA:Alk, and ammonia concentrations to the healthy range for methanogens (2017). Note that long lag periods were observed prior to the onset of rapid biogas production for both food waste and tea leaves (21 days) and food waste and compostable plates (30 days), indicating that substrate pretreatment or inoculum acclimation has the potential to accelerate the onset of biogas production (2019).

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In addition, biogas production for food waste and compostable plates did not stabilize over the 92-day digestion period, indicating that more biogas production was possible.

The results indicate that codigestion of food waste with high C/N substrates, tea leaves, or compostable plates can increase biomethane production. Similar results were reported in other studies of food-waste codigestion with yard waste or sewage sludge (2017). Goel et al (2001) were only able to achieve high methane yields from tea leaves when nutrients were added, indicating that food-waste addition provided nutrients for tea-leave digestion.

Effect of Mixing Ratio on Codigestion of Food Waste, Tea Leaves, and Compostable Plates

Phase 2 BMPs were carried out for 88 days with food waste:tea leaves:compostable plates at mixing ratios of 1:1:1 and 2:1:1 (Figure 2 and Table 3). The cumulative methane yield for food waste:tea leaves:compostable plates 1:1:1 (264 ml CH$_4$/g VS) was significantly higher than for food waste:tea leaves:compostable plates 2:1:1 (45 ml CH$_4$/g VS). Although both digestion sets achieved similar VS reduction, the lower food-waste content digestion set had a higher pH and a VFA:Alk ratio in the healthy range for methanogenesis (Table 3).

In contrast to Phase 1, ammonia concentrations were similar in all digestion sets, most likely due to the varying composition of the food waste (2020). Methane quality for food waste:tea leaves:compostable plates 1:1:1 was between 60 and 70 percent, indicating good methanogenic activity. Although 25 percent of the inoculum used in Phase 2 was digestate produced in Phase 1 codigestion sets, a 20-day lag period was still observed prior to rapid onset of methane production (Figure 2), which was similar to food waste:tea leaves in Phase 1 (Figure 1). Further long-term continuous AD studies are needed to understand the effect of microbial acclimation on methane production with tea leaves and compostable plates.

Table 3. Final Chemical Analysis Results for Phase 2 Biochemical Methane Potential Assays

Digestion Set	VS Reduction (%)	Final pH	Ammonia (mg/L)	VFA:Alk Ratio	Methane Quality (%)	Methane Yield (ml CH$_4$/g VS)
Inoculum	BD	8.06±0.02	32.46±9.72	0.0185±0.001	34±12	65.0 ±0.9
FW:TL:CP 1:1:1	63.7±1.7	7.86±0.02	39.95±0.17	0.0786±0.0004	36±2	279±1
FW:TL:CP 2:1:1	66.1±8.9	4.84±0.01	46.21±1.60	4.57±0.008	46±9	59.5±4.1

Conclusion

Anaerobic codigestion of food waste with either compostable plates or tea leaves increased methane yields compared with AD of food waste on its own. Codigestion of high C/N substrate with food waste prevented inhibition by VFA and ammonia accumulation. Codigestion of food waste with both tea leaves and compostable plates resulted in high biomethane production when the ratio of food waste:tea leaves:compostable plates was maintained in the correct range.

The results indicate that food waste, tea leaves, and SCB-based compostable tableware can be collected from restaurants and cafeterias as a single-waste stream, avoiding the need to separate these materials prior to AD. The project also demonstrates a successful collaboration between a university and nearby industry to divert organic waste from landfills and incineration and improve bioenergy production.

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Data Availability

Datasets related to this article can be found at https://scholarcommons.usf.edu/etd/8274/.

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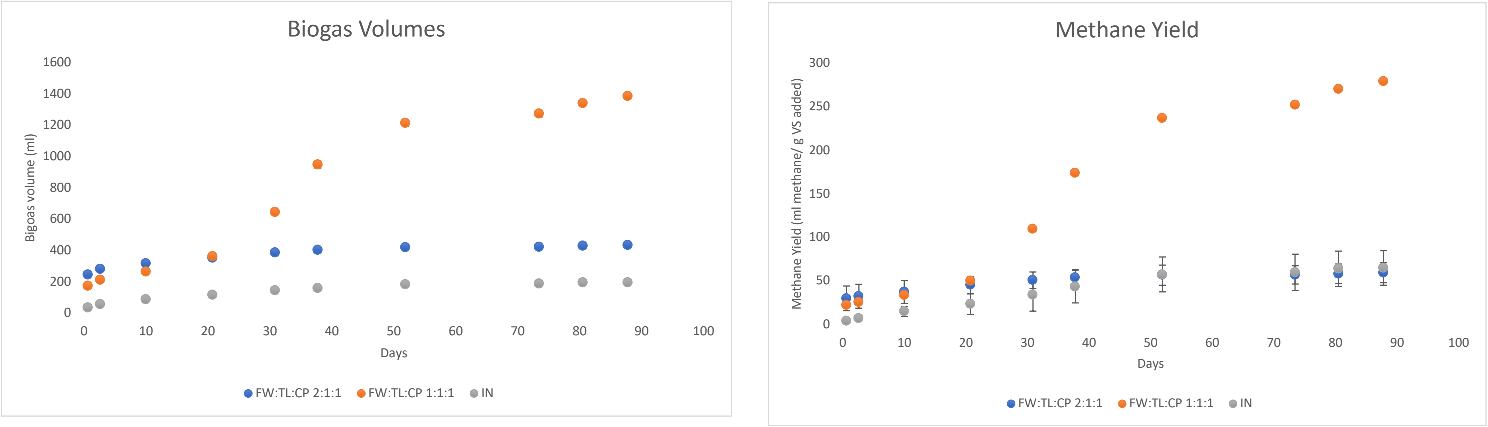

Figure 3. a) Cumulative biogas volume and b) methane yields (normalized to g/volatile solids added) for Phase 2 biochemical methane potential assays.

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