2024

Optimizing Anaerobic Digestion of Food Waste and Industrial Sludge for Biogas Production

Emma R. Murray
Georgia Southern University

Optimizing Anaerobic Digestion of Food Waste and Industrial Sludge for Biogas Production

An Honors Thesis submitted in partial fulfillment of the requirements for Honors in *Civil Engineering.*

By
Emma R. Murray

Under the Mentorship of Dr. L. Stetson Rowles

ABSTRACT

Food waste is a major contributor to municipal solid waste, and its disposal at landfills has significant environmental and economic impacts. Opportunities need to be identified for the sustainable management of food waste at large scales. Pulp and paper mills throughout the country commonly use anaerobic digestion to treat their waste sludge; however, this sludge can consist of over 50% lignin, which is slowly or negligibly digested. This research aims to explore the sustainability of co-digestion of food waste and paper mill sludge. Lab-scale studies were used to assess the feasibility of anaerobic digestion by measuring treatment efficiencies and biogas production. Results demonstrate that adding food waste to pulp and paper mill sludge increased methane production by 103% compared to anaerobically digested pulp and paper mill sludge on its own. The results from this work demonstrate how food waste can be diverted from landfills, while potentially providing paper mills with the opportunity to enrich their sludge for better digestion and increased biogas production.

Thesis Mentor: Dr. L. Stetson Rowles
Honors Dean: Dr. Steven Engel

April 2024
Allen E. Paulson College of Engineering and Computing

Honors College
Georgia Southern University

Acknowledgments

I would like to thank several people and organizations for their continuous support during my time at Georgia Southern.

Dr. Rowles, thank you for always making time to answer any questions I had and for being such a great role model. Thank you to Dr. Francisco Cubas and Dr. Asli Aslan for your contributions to this project. Nizam Uddin and Cassidy Hartog, thank you both for working so hard on developing this project. To my parents and sister, thank you for your never-ending love and support during these past four years.

Thank you to the Environmental Protection Agency for assisting in the funding and development of this project. Lastly, thank you to the Georgia Southern Honors College for allowing me the opportunity to pursue this research.

1.0 Introduction

Food waste (FW) is a significant contributor to municipal solid waste, resulting in major environmental and economic consequences when disposed of in landfills.[1] In the United States alone, an estimated 103 million tons of food were wasted in 2018.[2] As seen in Figure 1 below, the disposal of FW in landfills can also lead to the release of methane, which has a considerable impact on the environment. Wasted food breaks down quickly which generates methane, which is detrimental to the environment as it contributes to global warming potential. However, when methane is captured, it can be burned for heat and to generate energy through the use of combined heat and power units.[6] Universities and colleges in the US are significant food wasters due to overproduction, imperfect inventory management, and fluctuations in sales. On average, each student meal generates an estimated 0.20-0.70 kg of wasted food.[2-5] We need to find opportunities for large-scale and sustainable disposal of FW from universities.

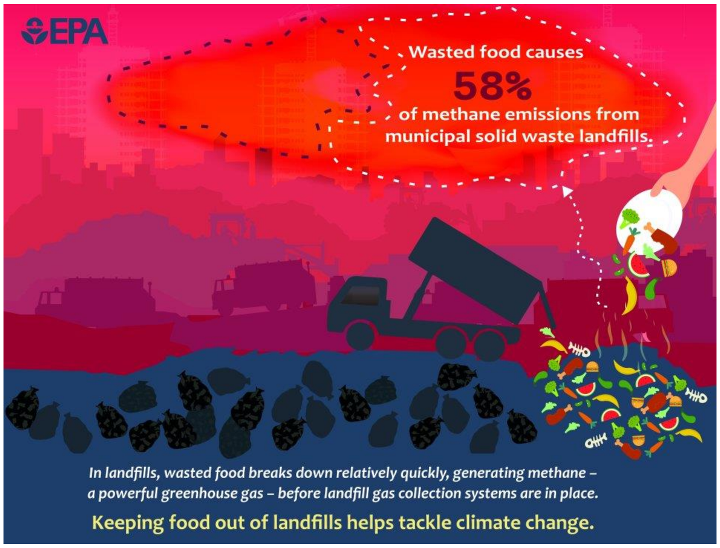

Figure 1: Depiction of Methane Production at Landfills.[6]

Another source of a large amount of waste is the production of paper from pulp and paper mills. In the US, the benchmark for water use at pulp and paper mills is approximately 17,000 gallons/ton of paper.[7] These water-intensive factories usually treat their wastewater onsite and generate waste sludge. Many of them commonly use anaerobic digestion to manage the generated waste and reduce effluent loads. However, this sludge can consist of over 50% lignin, which is slowly or negligibly digested. Additionally, using anaerobic digestion only for the effluent water provides obstacles such as variations in the wastewater composition and the occurrence of anaerobic inhibitors such as acids.[8] These limitations lead to a potentially synergistic solution for sustainable handling of both FW and pulp and paper mill waste. This approach not only provides a means for the disposal of FW but also offers advantages to the paper mill itself. By incorporating FW as a feedstock, the digestibility and production of biogas at the mill could potentially increase. The biogas produced could be harnessed on-site to generate heat or electricity for other aspects of the paper-making process, providing an economic benefit for the mill. This research seeks to identify a new option for the sustainable management of FW that can be quickly implemented across the US by leveraging existing infrastructure. Figure 2 shows the co-location of large universities and paper mills in the US. Specifically, this research will explore the feasibility of co-digestion of FW and paper mill sludge utilizing the current anaerobic infrastructure.

In order to explore this synergistic opportunity for both universities and pulp and paper mills, biochemical methane potential (BMP) experiments can provide the first step to explore the feasibility. Completing these batch BMP experiments gives preliminary data regarding both the pulp and paper mill sludge (PPMS) and the FW. These results yield insight into what results could be on a much larger scale. Limitations of these experiments can include the inability to gather information on chronic toxicity due to the high proportion of sludge in the mixture and the substance being only fed once at the beginning of the experiment.

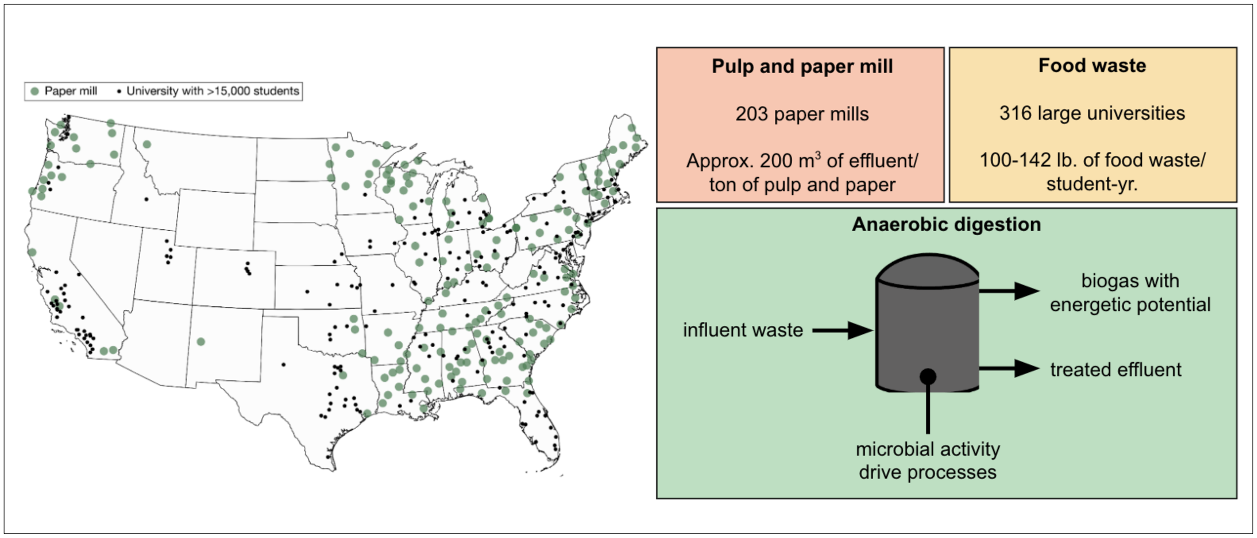

Figure 2: Co-location of paper mill locations and universities to demonstrate potential opportunities of scale (left).[24-25] Scale of pulp and paper mills and food waste from universities along with overview of the anaerobic digestion process (right).

The overall goal of my thesis research was to produce and capture biogas from the anaerobic digestion of FW and PPMS. This research has been completed through the development of batch-scale experiments to quantify biogas production and digestion of sludge. This research has the potential to be developed further through experimentation to discover the best methods for the highest methane yield. The results may be of interest to universities and pulp and paper mills in the US as a way of decreasing their landfill waste while also capturing methane that can be used to produce heat and energy.

2.0 Materials and Methods

2.1 Measuring biomethane potential through batch experiments.

2.1.1 Preliminary Experimental Setup. For the preliminary design, a set of batch reactors was used to ensure the setup would produce methane and that it could be captured correctly. Laboratory scaled reactors (batch reactors) simulating anaerobic digesters were used in this study.[9,10] Specifically, 1 L GL45 media bottles were used to perform the experiments. They were sealed to the atmosphere, purged with nitrogen gas, and placed in a temperature-controlled water bath simulating mesophilic conditions (35ºC ± 2ºC). As seen in Figure 2, a tube connecting the initial reactor with a second bottle containing 3N NaOH allowed the produced biogas (a mixture of methane and carbon dioxide) to flow into it. The carbon dioxide dissolved in the 3N NaOH which allowed the methane to cause the liquid to displace into a third bottle. The displaced liquid was used to volumetrically measure the methane produced daily.

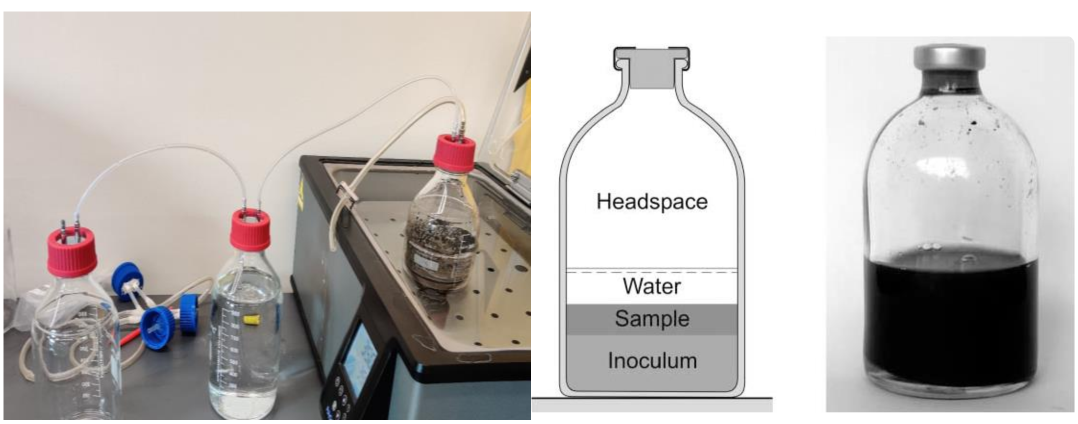

Figure 3: Experimental setup showing batch reactor in a temperature-controlled water bath and liquid displacement bottle for measuring produced biomethane (left). Schematic describing parameters in digesters (right).[9]

2.1.2 First round of batch experiments. After ensuring that the reactors were producing methane and the setup was correct, a 38-day experiment was conducted to measure biomethane potential and ensure sludge acclimation.[10,11] For this experiment, 5 batch reactors were tested – three for the combination of FW and pulp and paper mill sludge (FW+PPMS) and two for PPMS. The ratios and volume of each parameter can be found in Table 1 below. Before mixing, the PPMS, the inoculum, and the FW were all tested separately for several parameters. Total solids (TS) and volatile suspended solids (VSS) were measured by the standard methods 2540 (APHA 2012). A pH meter (Model F20, Mettler Toledo) was used to measure pH. Chemical oxygen demand (COD), volatile fatty acids (VFA), and total ammonia nitrogen (TAN) were measured using a DR1900 spectrophotometer with TNT methods 822, 872, and 830 respectively. Total organic carbon (TOC) and total nitrogen (TN) were measured using a total organic carbon analyzer.[12] After the experiment, the digestate was characterized based on the same parameters.

Table 1: First Experiment Reactor Specifications

Ratio of PPMS: FW	Number of Reactors	Volume of Seed (mL)	Volume of PPMS (mL)	Volume of FW (mL)
1:0	2	200	400	0
2:1	3	200	267	133

2.1.3. Second round of batch experiments. To help understand reproducibility, a 35-day experiment was conducted using 5 batch reactors. This experiment's parameters were tested similarly to the first experiment. The ratios and volume of each parameter can be found in Table 2 below. After the experiment was complete, these same parameters were measured once again.

Table 2: Second Experiment Reactor Specifications

Number of Reactors	Volume of Seed (mL)	Ratio and Volume of PPMS to DI Water (mL)	Ratio and Volume of FW to DI Water (mL)
5	310	50 mL PPMS: 50 mL DI Water	42 mL FW: 58 mL DI Water

3.0 Results and Discussion

3.1 Methane Production and Characterization from Initial Experiments

The first round of experiments aimed to determine if PPMS alone could generate methane, and how the addition of FW would impact methane production. Figure 4 illustrates that PPMS on its own did not yield any substantial quantity of methane. In contrast, reactors containing a blend of FW and PPMS began producing significant amounts of methane after an initial lag phase of approximately 12 days. These findings align with prior research on anaerobic co-digestion of similar feedstocks, which has demonstrated improved methane yields when FW is combined with other organic substrates.[13] The initial lag phase observed in this study is likely due to the time required for the microbial community to acclimate to the new feedstock and environmental conditions within the reactor. Despite this lag, the ultimate methane yield achieved highlights the potential synergies of co-digesting FW and PPMS.

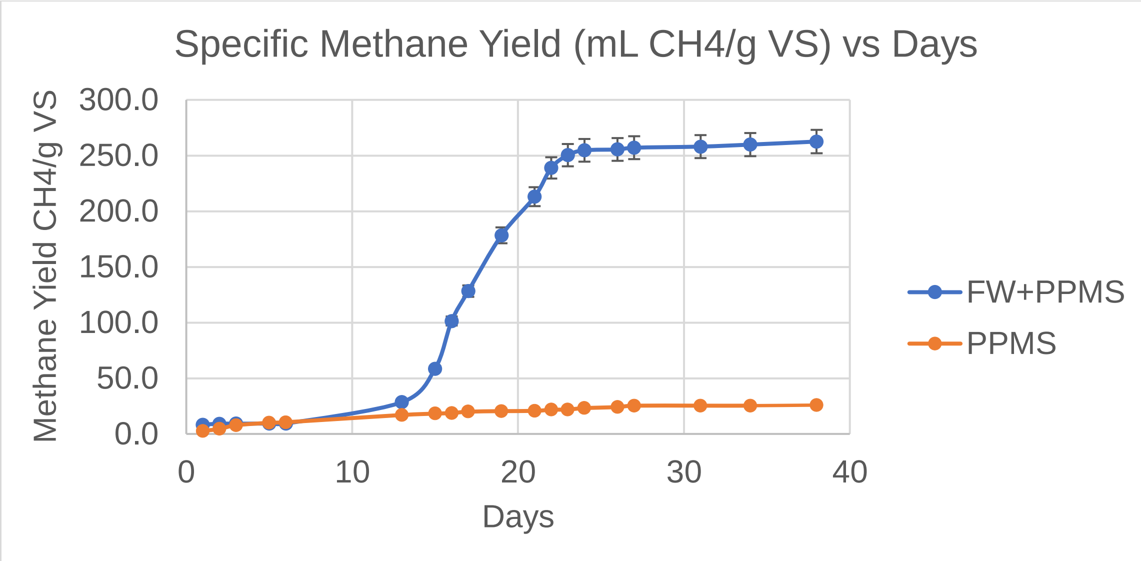

Figure 4 Specific methane yield of the co-digestion of food waste (FW) and pulp and paper mill sludge and mono-digestion of only PPMS (PPMS). Error bars represent standard error of triplicate reactors.

Table 3 presents the characterization of the individual waste streams (top) and the digestate from each reactor (bottom) before and after the first round of experiments, respectively. The primary objective of this initial trial was to confirm that the experimental setup was functioning as intended, with the reactors generating methane that could be effectively captured and quantified. Upon analyzing the pre- and post-characterization data, a substantial reduction in COD was observed. The FW, which initially had a COD of over 61,000 mg/L, exhibited a dramatic decrease to approximately 1,300 mg/L when co-digested with PPMS. This significant reduction in COD indicates that the organic matter present in the FW was effectively broken down and converted during the anaerobic digestion process. The marked decrease in COD is a key finding, as it suggests that the volatile solids in the feedstock were successfully removed and likely converted to biogas.[14] Volatile solids reduction is a primary indicator of the efficiency of anaerobic digestion systems, as it directly correlates with the amount of organic matter that has been stabilized and converted into methane.[15] The results from this initial experiment demonstrate that the co-digestion of FW and PPMS not only produces methane but also achieves substantial reductions in organic loading, highlighting the potential for this approach to effectively treat these waste streams.

Table 3: Pre- and post-characterization of reactors.

Pre-Characterization						
	pH	COD (mg/L)	TN (mg/L)	TOC (mg/L)	TS (g/L)	VSS (g/L)
PPMS	6.9	939.7	198.25	109.3	77.78	23.73
Inoculum	7.49	1884.4	1633	294.175	13.77	4.15
FW	4.05	61016.9	606.25	18642.5	29.94	11.8

Post-Characterization							
	pH	COD (mg/L)	NH_3-N (mg/L)	VFA (mg/L CH_3COOH)	Alkalinity (mg/L $CaCO_3$)	TS (mg/L)	VS (mg/L)
FW+PPMS	7.5	1324	1026	468	2905.5	33.2	11.3
PPMS	7.46	699.9	756	297	1821	25.8	10

3.2 Methane Production and Characterization from Replicate Experiments

Following the promising results from the first round of experiments, an additional round of experiments was conducted to investigate the factors contributing to the observed initial lag phase during the first 10 days of the digestion process. This lag phase, characterized by minimal methane production, was consistently observed in both the first and second rounds of experiments, as evidenced by similar trends in methane yield over time (Figures 4 and 5). Several factors could potentially explain this initial lag phase. One hypothesis is that the microbial community requires time to adapt to the new substrate and environmental conditions within the reactor. When FW and PPMS are first introduced, the existing microbial population may not be optimally suited to efficiently break down these specific organic materials. As a result, there may be a period of microbial acclimation and selection, during which the community structure shifts to favor microorganisms that are better equipped to hydrolyze and ferment the complex organic compounds present in the feedstock.[16]

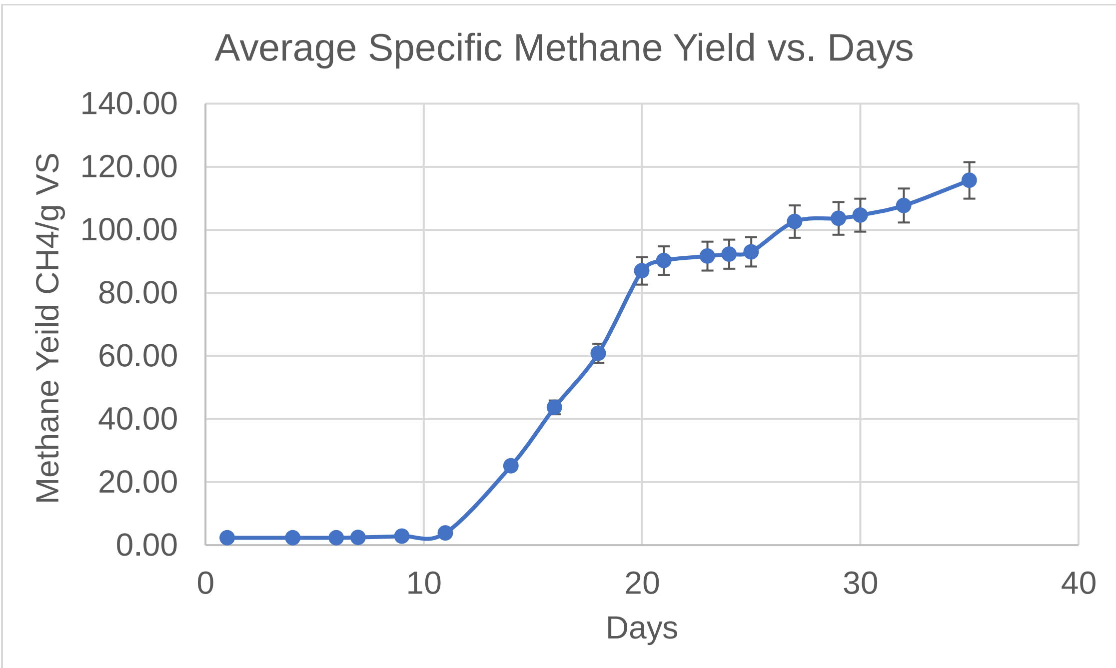

Figure 5: Average specific methane yield of the co-digestion of food waste and pulp and paper mill sludge. Error bars represent standard error of triplicate reactors.

Another potential factor contributing to the lag phase is the initial pH of the reactor contents. As seen in Table 4, the pre-characterization of the blended FW and PPMS revealed a slightly acidic pH of 5.8. This acidic environment could temporarily inhibit the activity of methanogens, the microorganisms responsible for the final stage of anaerobic digestion and the production of methane. Methanogens are known to be sensitive to pH fluctuations and have a preferred range of 6.5 to 8.2 for optimal growth and methane production.[17] The team hypothesizes that the observed lag phase may be attributed to the time required for the reactor pH to naturally stabilize and reach a more favorable range for methanogenic activity.

Additionally, the lag phase could be influenced by the initial concentrations of VFAs in the feedstock. During the early stages of anaerobic digestion, complex organic matter is hydrolyzed and fermented into VFAs such as acetate, propionate, and butyrate.[18] While VFAs are important intermediates in the methanogenic pathway, high concentrations can lead to a decrease in pH and inhibit methanogenesis. The pre-characterization data in Table 3 shows an initial VFA concentration of 1,458 mg/L in the blended feedstock. This relatively high VFA concentration may contribute to the temporary inhibition of methanogens and the observed lag in methane production. As the digestion process progresses, the pH of the reactor contents tends to stabilize due to the consumption of VFAs by methanogens and the natural buffering capacity of the system. This stabilization, coupled with the acclimation of the microbial community, likely explains the gradual increase in methane production observed after the initial lag phase.[19]

To better understand the factors governing the lag phase and optimize the co-digestion process, future research should focus on characterizing the microbial community structure and dynamics throughout the digestion process. This could be achieved through the application of molecular biology techniques such as 16S rRNA gene sequencing or metagenomics. Additionally, more frequent monitoring of key parameters such as pH, VFAs, and alkalinity during the early stages of digestion could provide valuable insights into the factors contributing to the lag phase and guide strategies for process optimization, such as pH control or staged feedstock introduction.

In summary, the consistent observation of an initial lag phase in methane production during the co-digestion of FW and PPMS can be attributed to a combination of factors, including microbial acclimation, initial pH, and VFA concentrations. Understanding and addressing these factors will be crucial for optimizing the anaerobic co-digestion process and maximizing methane yields in future studies and full-scale applications.

Table 4: Pre- and Post-Characterization of Reactors

Pre-Characterization							
Sample No.	**pH**	**TS**	**VS**	**COD**	**VFA**	**Alkalinity**	**NH3-N**
		(g/L)	**(% of TS)**	**(mg/L)**	**(mg/L CH3-COOH)**	**(mg/L as CaCO3)**	**(mg/L)**
FW+PPMS 1	5.57	37	64.9	9060	4275	3861	0.51
FW+PPMS 2	5.64	41	63.4	11070	3957	3993	0.549
FW+PPMS 3	5.66	41	63.4	9720	4188	3204	0.843
FW+PPMS 4	5.63	34	58.8	10800	4299	3696	0.552
FW+PPMS 5	5.65	38	60.5	11940	4518	3666	0.588

Post-Characterization							
Sample No.	**pH**	**TS**	**VS**	**COD**	**VFA**	**Alkalinity**	**NH3-N**
		(g/L)	**(% of TS)**	**(mg/L)**	**(mg/L CH3-COOH)**	**(mg/L as CaCO3)**	**(mg/L)**
FW+PPMS 1	7.22	29	51.72	604	804	3382	0.55
FW+PPMS 2	7.16	29	51.72	738	1024	3672	0.656
FW+PPMS 3	7.21	28	57.14	648	1404	4082	0.592
FW+PPMS 4	7.17	28	53.57	720	820	3542	0.606
FW+PPMS 5	7.28	23	52.17	796	722	4212	0.596

4.0 Environmental Implications

The co-digestion of FW and PPMS offers a sustainable solution to mitigate the environmental impacts associated with the disposal of these organic waste streams.[20] By diverting FW from landfills and integrating it into the anaerobic digestion process at pulp and paper mills, this approach can significantly reduce greenhouse gas emissions, conserve landfill space, and minimize the potential for groundwater contamination.[21] The capture and utilization of methane produced during the digestion process not only prevents the release of this potent greenhouse gas into the atmosphere but also provides a renewable energy source that can offset the consumption of fossil fuels. Furthermore, the nutrient-rich digestate produced during anaerobic co-digestion can be used as a soil amendment in agricultural settings, reducing the need for synthetic fertilizers and promoting sustainable nutrient management practices.[22]

The successful implementation of anaerobic co-digestion in pulp and paper mills exemplifies the principles of a circular economy, where waste streams are valorized, and resources are used efficiently. The scalability and replicability of this approach present an opportunity for widespread environmental benefits, as more facilities adopt this technology. Moreover, the findings of this research have important policy implications, as they can inform waste management strategies, renewable energy policies, and greenhouse gas emission reduction targets. By aligning policies with the principles of waste valorization and resource efficiency, governments can create an enabling environment for the widespread implementation of anaerobic co-digestion, contributing to a more sustainable and resilient future.[23]

5.0 Future Work

- Microbial community analysis: To gain a deeper understanding of microbial dynamics and their influence on the co-digestion process, future research should incorporate advanced molecular biology techniques such as 16S rRNA gene sequencing, metagenomics, and metatranscriptomics. These analyses can provide valuable insights into the composition, diversity, and functional potential of the microbial communities involved in anaerobic co-digestion, enabling the identification of key microbial players and potential process bottlenecks.
- Pretreatment methods: Investigating various pretreatment methods for FW and PPMS can potentially enhance the efficiency and performance of the co-digestion process. Future studies should explore the effects of mechanical, thermal, chemical, and biological pretreatment techniques on substrate biodegradability, biogas yield, and process kinetics. Identifying optimal pretreatment strategies can help maximize the energy recovery potential of the co-digestion process.
- Digestate valorization: Future research should focus on exploring the potential applications and valorization pathways for the digestate produced during anaerobic co-digestion. This can include assessing the nutrient content, heavy metal concentrations, and microbial safety of the digestate, as well as evaluating its suitability for use as a soil amendment or fertilizer. Additionally, investigating the potential for further processing of the digestate, such as composting or nutrient recovery, can add value to the co-digestion process and promote a circular economy approach.

- Continuous anaerobic digestion: To further validate the findings of this study and assess the long-term stability and performance of the co-digestion process, future research should focus on conducting continuous anaerobic digestion experiments. These experiments should aim to investigate the effects of varying organic loading rates, hydraulic retention times, and substrate mixing ratios on biogas production, process stability, and digestate quality.
- Collaboration with industry partners: Establishing collaborations with local FW generators, such as restaurants, grocery stores, and food processing facilities, as well as pulp and paper mills, is crucial for the successful implementation of the co-digestion technology. Future work should involve engaging with these industry partners to assess the quantity and quality of available feedstocks, identify potential barriers to adoption, and develop pilot projects that demonstrate the feasibility and benefits of the co-digestion process in real-world settings.

References

(1) Hall, K. D.; Guo, J.; Dore, M.; Chow, C. C. The Progressive Increase of Food Waste in America and Its Environmental Impact. *PLoS One* **2009**, *4* (11), e7940. https://doi.org/10.1371/JOURNAL.PONE.0007940.

(2) US EPA. 2018 Wasted Food Report. Estimates of Generation and Management of Wasted Food in the United States in 2018. **2020**.

(3) Ebner, J.; Win, S. S.; Hegde, S.; Vadney, S.; Williamson, A.; Trabold, T. Estimating the Biogas Potential From Colleges and Universities. *ASME 2014 8th Int. Conf. Energy Sustain. ES 2014 Collocated with ASME 2014 12th Int. Conf. Fuel Cell Sci. Eng. Technol.* **2014**, *2*. https://doi.org/10.1115/ES2014-6433.

(4) Mu, D.; Horowitz, N.; Casey, M.; Jones, K. Environmental and Economic Analysis of an In-Vessel Food Waste Composting System at Kean University in the U.S. *Waste Manag.* **2017**, *59*, 476–486. https://doi.org/10.1016/J.WASMAN.2016.10.026.

(5) Whitehair, K. J.; Shanklin, C. W.; Brannon, L. A. Written Messages Improve Edible Food Waste Behaviors in a University Dining Facility. *J. Acad. Nutr. Diet.* **2013**, *113* (1), 63– 69. https://doi.org/10.1016/J.JAND.2012.09.015.

(6) US EPA, ORD. “Quantifying Methane Emissions from Landfilled Food Waste.” Www.epa.gov, 12 Oct. 2023, www.epa.gov/land-research/quantifying-methane-emissions-landfilled-food-waste.

(7) Ryberg, Alaina. MnTAP – Water Use. www.mntap.umn.edu/industries/facility/paper/water/#:~:text=The%20US%20benchmark%20for%20water.

(8) Meyer, T., & Edwards, E. A. (2014). Anaerobic digestion of pulp and paper mill wastewater and sludge. Water Research, 65, 321–349. https://doi.org/10.1016/j.watres.2014.07.022

(9) Angelidaki, Irini & Bolzonella, Madalena & Borzacconi, David & Campos, Liliana & Guwy, Luis & Jenícek, Alan & Kalyuzhnui, Pavel & Van, Sergey. Anaerobic Biodegradation, Activity and Inhibition (ABAI).

(10) Hagelqvist, A.; Granström, K. Co-Digestion of Manure with Grass Silage and Pulp and Paper Mill Sludge Using Nutrient Additions. Environ. Technol. (United Kingdom) 2016, 37 (16), 2113–2123. https://doi.org/10.1080/09593330.2016.1142000.

(11) Hinds, G. R.; Mussoline, W.; Casimir, L.; DIck, G.; Yeh, D. H.; Ergas, S. J. Enhanced Methane Yields in High-Solids Anaerobic Digestion Through Inoculation with Pulp and Paper Mill Sludge. *Environ. Eng. Sci.* **2016**, *33* (11), 907–917. https://doi.org/10.1089/ees.2016.0129.

(12) American Water Works Association and Water Environment Federation. *Standard*

(13) T, M.; EA, E. Anaerobic Digestion of Pulp and Paper Mill Wastewater and Sludge. *Water Res.* **2014**, *65*, 321–349. https://doi.org/10.1016/J.WATRES.2014.07.022.

(14) Mussoline, W.; Esposito, G.; Lens, P.; Spagni, A.; Giordano, A. Enhanced Methane Production from Rice Straw Co-Digested with Anaerobic Sludge from Pulp and Paper Mill Treatment Process. *Bioresour. Technol.* **2013**, *148*, 135–143. \https://doi.org/10.1016/J.BIORTECH.2013.08.107.

(15) Mei, R. et al. (2016) 'Evaluating digestion efficiency in full-scale anaerobic digesters by identifying active microbial populations through the lens of microbial activity', Scientific Reports, 6(1). Available at: https://doi.org/10.1038/srep34090.

(16) Llamas, M., Greses, S., Magdalena, J. A., González-Fernández, C., & Tomás-Pejó, E. (2023). Microbial co-cultures for biochemicals production from lignocellulosic biomass: A Review. Bioresource Technology, 386, 129499. https://doi.org/10.1016/j.biortech.2023.129499

(17) Carotenuto, C., Guarino, G., Morrone, B., & Minale, M. (2016). Temperature and ph effect on methane production from Buffalo Manure Anaerobic Digestion. International Journal of Heat and Technology, 34(S2). https://doi.org/10.18280/ijht.34s233

(18) Llamas, M., Greses, S., Magdalena, J. A., González-Fernández, C., & Tomás-Pejó, E. (2023). Microbial co-cultures for biochemicals production from lignocellulosic biomass: A Review. Bioresource Technology, 386, 129499. https://doi.org/10.1016/j.biortech.2023.129499

(19) Lendormi, T., Jaziri, K., Béline, F., Le Roux, S., Bureau, C., Midoux, C., Barrington, S., & Dabert, P. (2022). Methane production and microbial community acclimation of five manure inocula during psychrophilic anaerobic digestion of swine manure. Journal of Cleaner Production, 340, 130772. https://doi.org/10.1016/j.jclepro.2022.130772

(20) Mudzanani, K., Iyuke, S. E., & Daramola, M. O. (2022). Co-digestion of wastewater treatment sewage sludge with various biowastes: A Comparative Study for the enhancement of biogas production. Materials Today: Proceedings, 65, 2172–2183. https://doi.org/10.1016/j.matpr.2022.05.539

(21) Rama, H., Akindolire, M., Obi, L., Bello-Akinosho, M., Ndaba, B., Dhlamini, M. S., Maaza, M., & Roopnarain, A. (2023). Anaerobic digestion: Climate change mitigation through sustainable organic waste valorization. Handbook of Nature-Based Solutions to Mitigation and Adaptation to Climate Change, 1–19. https://doi.org/10.1007/978-3-030-98067-2_7-1

(22) Chojnacka, K., & Moustakas, K. (2024). Anaerobic digestate management for carbon neutrality and fertilizer use: A review of current practices and future opportunities. Biomass and Bioenergy, 180, 106991. https://doi.org/10.1016/j.biombioe.2023.106991

(23) Choong, Yee Yaw, et al. "Impacts of Trace Element Supplementation on the Performance of Anaerobic Digestion Process: A Critical Review." Bioresource

Technology, vol. 209, June 2016, pp. 369–379, https://doi.org/10.1016/j.biortech.2016.03.028.

(24) "Maps | Data Basin." Databasin.org, databasin.org/maps/new/#datasets=1f2a22ee1aa441568cbf5bea1b275c88. Accessed 25 Apr. 2024.

(25) "Digest of Education Statistics, 2017." Nces.ed.gov, nces.ed.gov/programs/digest/d17/tables/dt17_312.20.asp. Accessed 25 Apr. 2024.