Evaluating and Optimizing the Value of Anaerobic Digestion of Food Waste using Sensitivity Analysis and Machine Learning

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Hinkley Center

Full Proposal

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Abstract

Food waste (FW) is one of the largest fractions of wet-organic waste, with an estimated one third of all food produced for human consumption wasted globally (FAO, 2011). In the U.S., 35 million of tons of FW is landfilled representing a significant resource and economic loss (EPA, 2020). Anaerobic digestion (AD) is a biological conversion process that can be used as an alternative to landfilling to reduce negative environmental impacts and support resource recovery from FW (Cruz et al, 2012; Choi et al., 2022). Two major limitations to the adoption of AD technology include economic viability (Cruz et al, 2022), and variability of the FW substrate. For low volumes of waste, the capital cost associated with AD and biogas upgrading can outweigh the potential value of the biogas. However, AD has been gaining increasing attention due to recent policy and economic incentives aimed at reducing GHG emissions by either diverting FW from landfills or incentivizing renewable natural gas (RNG) production. In addition, the inherent compositional variability and heterogeneity of FW (e.g., carbohydrate, protein, lipid content) can have a significant effect on AD performance and stability. Therefore, this project aims to advance the state-of-the-art of AD of FW by evaluating the variability and uncertainty of AD performance as a function of feedstock composition and operating parameters, and to develop a predictive tool that can estimate AD performance and corresponding system level cost and carbon footprint. These efforts will complement a feasibility study evaluating implementation of a full-scale FW digester in Gainesville. Results will be shared with local city and county officials and relevant industry stakeholders to aid in decision making to support sustainable post-consumer FW management.

I. Motivation/Background

The broad aim of this project is to advance the cutting-edge of wet-organic waste utilization via anaerobic digestion (AD) and to aid stakeholders in the development and implementation of AD systems for resource recovery from wet-organic waste. Specially, this project will evaluate the impact of municipal food waste (FW) compositional variability and AD operating parameters on process cost and carbon footprint, with consideration of other locally available wet-organic waste as potential co-digestion substrates (Figure 1).

Wet-organic wastes including food waste, wastewater biosolids, and manure, among others, represent a significant and underutilized resource that could be leveraged to support a circular bioeconomy approach to generate valuable biobased products including biofuels, biomaterials, and biobased chemicals (Kirtikumar and Bhalchandra, 2018). FW is one of the largest fractions of wet-organic waste, with an estimated one-third of all food produced for human consumption wasted globally (FAO, 2011). In the U.S., 35 million of tons of FW is landfilled representing a significant resource and economic loss (EPA, 2020). AD is a biological conversion process that can be used as alternative to landfilling to reduce potential negative environmental impacts and support resource recovery from FW (Cruz et al, 2012; Choi et al., 2022). AD is a naturally occurring process in which complex organic matter is broken down via the concerted, metabolic interaction actions of various groups of microorganisms in the absence of oxygen to produce biogas, a mixture of methane and carbon dioxide (Braguglia et al, 2018; Khanal, 2008). The process also produces a nutrient-rich digestate that could be utilized as a fertilizer, or leveraged to produce other biobased resources. The methane-rich biogas can be used as an alternative to natural gas for combined heat and power (CHP) or upgraded to pipeline quality renewable natural gas (RNG) or compressed natural gas (CNG) for vehicle use.

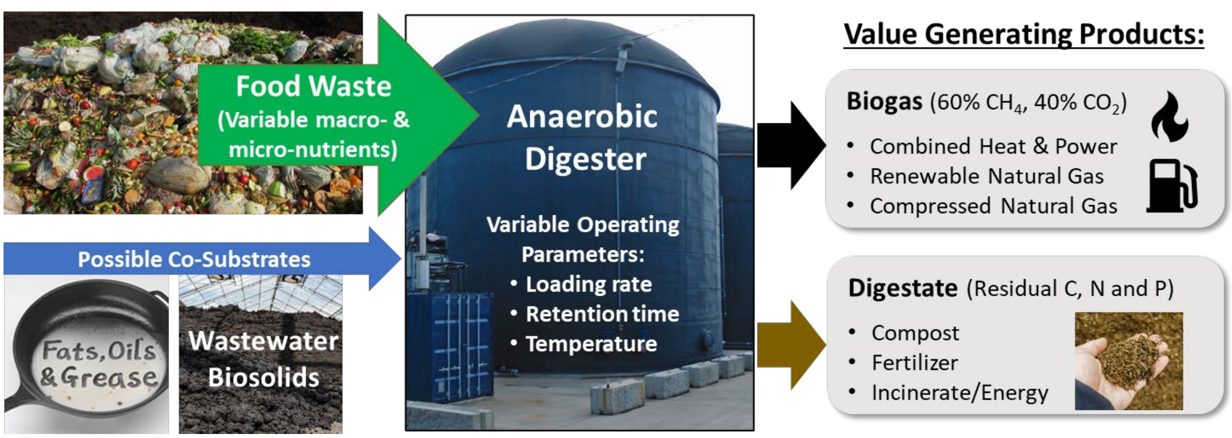

Figure 1. Overview of anaerobic digestion of food waste process and products generated (biogas and digestate), as well as possible co-digestion substrates that will be evaluated in the proposed study.

A major limitation to the adoption of AD technology is economic viability (Cruz et al, 2022). For low volumes of waste, the capital cost associated with AD and biogas upgrading can outweigh the potential value of the biogas, thus landfilling continues to be the most economic waste management option in the U.S. However, AD has been gaining increasing attention due to recent policy and economic incentives aimed at reducing GHG emissions by either diverting FW from landfills or incentivizing renewable natural gas (RNG) production (Dalke et al, 2021; Morales Polo et al, 2018). California has been a leader in these efforts with implementation of the Low Carbon Fuel Standard (Jossi, 2021). Locally, the City of Gainesville implemented a Zero Waste ordinance in May 2022 that will require restaurants to begin source separating FW for diversion from landfilling in June 2023 (City of Gainesville, 2022). This has created a pressing need for alternative FW management options in the City of Gainesville. According to local officials, the only current alternative to landfilling is a local composting facility, which will need to be expanded to meet the expected volume of FW to be collected. Besides that, according to EPA's Food Recovery Hierarchy (Figure 2) it would be preferential to divert FW to AD for energy recovery prior to composting or land application of the remaining digestate for nutrient recovery.

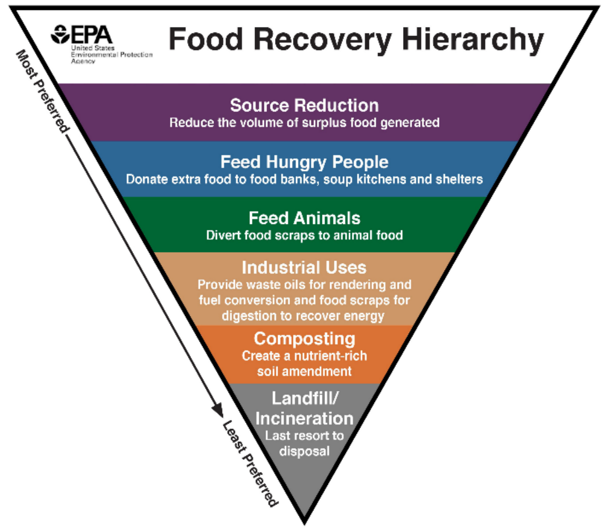

Figure 2. EPA's Food Recovery Hierarchy

The City of Gainesville had an initial economic analysis conducted by the National Renewable Energy Laboratory (NREL) which suggested that AD of residential and commercial FW with upgrading of the biogas to compressed natural gas (CNG) could provide greater profitability than composting or other biogas utilization options (Figure 3).

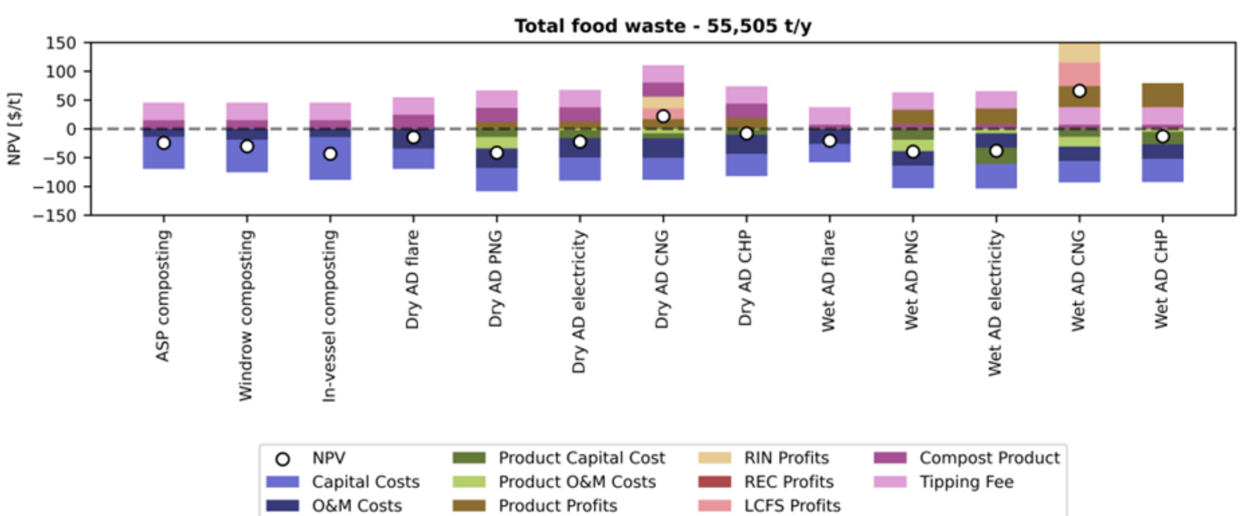

Figure 3. Initial results from NREL for the City of Gainesville estimating net present value (NPV) for community food waste composting and anaerobic digestion (AD) scenarios with various biogas upgrading options (PNG = Pipeline Renewable Natural Gas, CNG = Compressed Natural Gas, CHP = Combined Heat and Power).

The City has since secured DOE funding to carry-out a formal feasibility study and design plan for a full-scale digester to treat community FW in possible combination with fats, oils, and grease (FOG) and/or wastewater biosolids. To complement that feasibility study, City officials would like to understand the uncertainty and potential operational risks and mitigation strategies related to AD of FW, FOG and wastewater biosolids, which the proposed project aims to address.

II. Methodology/Scientific Approach

This project aims to advance the state-of-the-art of AD of FW by evaluating the variability and uncertainty of AD as a function of feedstock composition and operation parameters and develop a machine learning (ML) based framework to predict AD performance based on feedstock composition and operating parameters. Such a tool will aid industry, investors, planners, policy makers, and waste management operators in the development and operation of AD waste treatment systems. To develop the ML-based predictive tool, a detailed literature review will be carried out to (a) establish a dataset linking feedstock characteristics and AD operating parameters to AD performance metrics (e.g., methane production and digestate quality) and (b) identify potential operational risks that could arise during AD of FW in combination with other relevant feedstocks and mitigation strategies to overcome these risks. An economic sensitivity analysis will be performed to evaluate how feedstock composition and operational variation can impact the cost, and carbon footprint, of the AD process.

Specific research objectives include:

1. Establish a dataset linking feedstock characteristics and AD operating parameters, to AD performance metrics (e.g., methane production and digestate quality).
2. Develop a ML-framework to predict AD performance based on feedstock characteristics and operating parameters.
3. Conduct an economic sensitivity analysis to evaluate the impact of feedstock and process variation on carbon intensity and overall cost.

Objective 1 **– Establish a dataset linking feedstock characteristics, AD operating parameters, and AD performance metrics.**

Variation in terms of feedstock carbohydrate, protein, or lipid content can have a significant effect on AD reactor stability (Morales-Polo et al, 2018; Xu et al, 2018). Figure 4 is a simplified schematic of the Anaerobic Digestion Model Number 1 (ADM1), which shows the four stages of AD by which complex macromolecules are hydrolyzed into their soluble monomers (hydrolysis), converted into volatile fatty acids (VFAs) (acidogenesis) and acetate (acetogenesis), and then to the end products methane and carbon dioxide (methanogenesis) (Bastone, et al, 2002; Hagos et al, 2017; Braguglia et al, 2018; Filer et al, 2019; Paritosh et al, 2017). Each of these phases is carried out by a different group of microorganisms working in sequence, with the end-product of one group serving as the substrate for the next. This makes AD particularly sensitive to fluctuations in feedstock composition due to the delicate balance of metabolic intermediates that must be maintained to support a healthy, functional microbial community (Khanal, 2008; Cruz et al, 2022). By the time a problem or system imbalance is detected, it may require a significant amount of time and resource inputs to correct. Therefore, understanding and being able to predict how compositional variability of influent feedstocks may impact performance would enable greater process control and optimization (Morales-Polo et al, 2018).

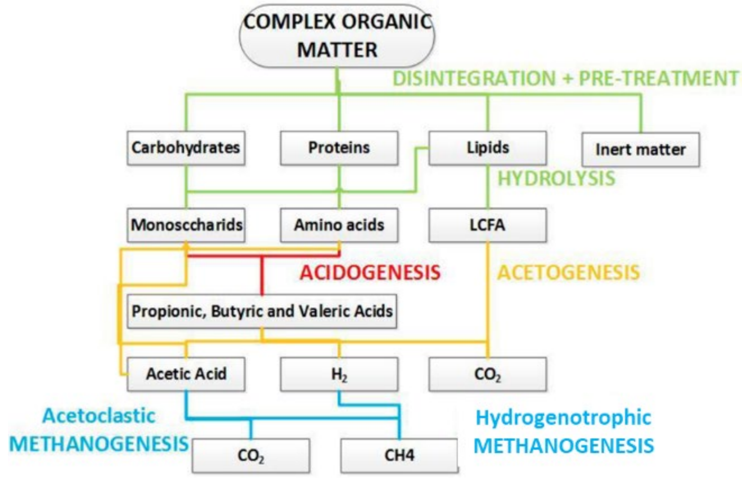

Figure 4. Simplified ADM1 schematic from Morales-Polo et al (2018).

Besides feedstock composition, there are several operating parameters that can also have a significant impact on process stability that must be considered in combination with feedstock composition to achieve optimal AD performance. These parameters include organic loading rate (OLR), retention time, temperature, pH, carbon to nitrogen ratio (C:N), particulate and dissolved solids content, among others. For example, a high OLR of easily degradable, carbohydrate-rich feedstocks such as fruits, vegetables and grains, can lead to process inhibition due to VFA accumulation and a drop in pH (Xu et al, 2018; Morales-Polo, et al 2018). Carbohydrate-rich feedstocks also tend to be low in nitrogen content, which can decrease reactor performance due to insufficient availability of nitrogen for microbial growth (Dalke et al, 202; Morales-Polo, et al 2018). In contrast, protein-rich foods, like dairy and meat products, tend to have a high nitrogen content, which can lead to process inhibition to due ammonia accumulation. Most reported FW mixtures are higher in carbohydrate content (10-61%) than protein (2.4-27%) (Morales-Polo et al, 2018; Dalke et al, 2021). Finally, feedstocks that are high in long chain fatty acids (LCFA), such as fats, oils, and grease (FOG) have a high theoretical methane potential, however, high loading rates of LCFA can cause process inhibition (Morales-Polo et al, 2018; Elsamadony et al, 2021). Current mitigation strategies include addition of commonly used additives such as cations and natural adsorbents (Elsamadony et al, 2021).

Co-digestion of FW with other more homogeneous, organic waste feedstocks is one strategy that could be employed to balance macro- and micro- nutrient concentrations (Morales-Polo et al, 2018; Karki 2021; Xu 2018). Wastewater biosolids, or sewage sludge, and animal manure are two locally available organic wastes that have been investigated as co-digestion substrates with FW (Dalke et al, 2021; Morales-Polo et al, 2018). Several studies reported an increased buffering capacity from ammonia during co-digestion of FW with sewage sludge (Kim et al, 2003; la Cour Jansen, 2004), as well as the ability to increase OLR (la Cour Jansen, 2004). Co-digestion of cow and pig manure with FW has been reported to improve trace element availability (Zhang, 2011; Zhang et al, 2013; Li et al, 2009), and co-digestion with cow manure and waste activated sludge have both been reported to improve C:N ratios leading to increased methane production from FW (Callaghan et al, 2002; Heo et al, 2004).

For the proposed study, an extensive literature review will be carried out to establish a dataset linking feedstock characteristics and operating parameters with AD performance metrics including methane production and digestate quality. The literature review will focus on collecting data related to AD of municipal or post-consumer FW, as well as co-digestion of FW with FOG and wastewater biosolids, as these are feedstocks of interest to the City of Gainesville.

***Objective 2* – Develop a ML-framework to predict AD performance based on feedstock characteristics and operating parameters.**

Recently, machine learning (ML) has gained significant attention as a tool for improving the monitoring, control, and optimization of AD processes. ML uses inductive inference to generalize correlations between input and output data, which is then used to make informed decisions under new circumstances (Cruz et at, 2022). Although various mechanistic models have been developed over the last decades to predict AD performance, including the commonly used ADM1 (Batstone, 2002), these models are often insufficient for predicting AD performance under real-world conditions given the complexity and variability of organic wastes and the AD microbial community. In the case of ADM1, calibrating the model parameters is challenging due to the complexity of microbial species and metabolic pathways involved (Batstone, 2002; Cruz et al 2022). Alternatively, ML offers a data-driven approach for predicting AD performance that can manage complex multivariate data, predict non-linear connections, and handle missing data (Cruz et al, 2022). ML may also be useful for solving problems such as seasonal availability of feedstocks, fluctuation in feedstock characteristics, and co-substrate ratio optimization (Cruz et al, 2022; De Clereq et al, 2020; Karki et al, 2021).

Several ML algorithms have been employed for modeling the AD process including artificial neural network (ANN), adaptive neuro-fuzzy interference system (ANFIS), k-nearest neighbors (KNN), random forest (RF), and support vector machine (SVM), with varying degrees accuracy and applicability. ANN has been one of the most used algorithms to predict biogas output and methane content based on substrate characteristics and various operating parameters (Beltramo et al, 2019; Neto et al, 2021; Seo et al, 2021; Senol et al, 2021). It has also been used to predict various parameters including optimum mixing ratios of co-substrates (Ghatak et al, 2018; Strik et al, 2005; Wang et al, 2018), and Zhang et al. (2019) proposed employing ANN to combine bioinformatics data from microbial communities with digesters' efficiency to improve the usage of massive metagenomics data. However, one limitation of ANN is that it converges slowly and readily falls into local optima (Dong and Chen, 2019). Combining ANN with an optimization technique such as genetic algorithm (GA) has been shown to overcome this limitation. The GA model can simultaneously evaluate several solutions in a search space, reducing the likelihood of falling into a local optimum (Guo et al, 2021). This combination has been applied in a few cases of AD of organic waste, with limited application in the context of FW AD (Beltramo et al, 2019; Cruz et al, 2022).

Using the data set established in Objective 1, this project will evaluate various ML algorithms/models including ANN + GA to develop a framework for predicting AD performance (e.g., methane production and digestate characteristics) from variable feedstock characteristics and operating parameters.

***Objective 3* – Conduct an economic sensitivity analysis to evaluate the impact of feedstock and process variation on carbon intensity and overall cost.**

The goal for this project is to understand how feedstock and operational viability may impact the economic feasibility of implementing a full-scale digester in the City of Gainesville. Thus, the data and predictive model developed in Objectives 1 and 2 will be integrated with a technoeconomic analysis (TEA) to estimated net present value for a potential full-scale AD system. The TEA will take into consideration various market pathways for the two products generated, namely biogas and digestate. The digestate, which is a slurry of undigested organic material and anaerobic biomass, contains a significant amount of nutrients (nitrogen and phosphorus). Depending on its characteristics, which are dependent on the influent feedstock characteristics and AD operating conditions, the digestate could be directly land applied as a fertilizer, or first dried and composted. Dry digestate is also sometimes used for animal bedding, or in some cases has been pelletized and incinerated for energy production. The value and any required downstream processing of the digestate will vary based on its characteristics coming out of the digester (Lamolinara et al, 2022).

In terms of the biogas, currently, the economic feasibility of AD projects is largely dependent on renewable energy credits coming from the federal Renewable Fuel Standard (RFS) and California's Low Carbon Fuel Standard (LCFS). To qualify for these credits, projects must demonstrate a certain level of greenhouse gas (GHG) emissions reduction, or carbon intensity (CI) reduction. In the case of the RFS, biogas generated from organic waste including food waste falls in the D5 RINs credit category and must demonstrate a 50% reduction in GHG emissions (EPA, 2023). For the LCFS, each year California's Air Resource Board sets a CI benchmark for all fuels, and fuels that can demonstrate a CI below the target level are able to generate credits. Upgrading of AD biogas to compressed natural gas for use as a transportation fuel can generate both RINs and LCFS credits.

Using sensitivity analysis, this project will evaluate the impact of feedstock characteristics and AD operational variation on carbon intensity and the resulting economics for full-scale AD of FW and co-digestion with FOG and/or wastewater biosolids. The impact of feedstock and operational variation on biogas and digestate production and quality will be evaluated with consideration of various biogas and digestate utilization pathways.

III. Statement of Novelty

Application of ML models to waste treatment and bioprocessing is just emerging as an area of research. Given the heterogeneous biochemical make-up of FW, as well as the complexity of the AD process and microbial community involved, current mechanistic models are insufficient for accurately predicting AD outcomes under variable real-world conditions. Thus, this project will advance the leading-edge of research to enable transformative improvements in AD process predictability, optimization, and control. The ML component of the project will be a new convergent area of research between PI Martin-Ryals and Co-PI Bliznyuk.

In addition, this project will generate an extensive dataset linking feedstock characteristics, operating parameters, and AD performance metrics (e.g., biogas and digestate production and quality). Advancements in modeling are often limited by the availability of high quality, comprehensive data sets. This project will address that limitation and create a novel data set that will be made available to other researchers via the project website and publication.

This project will generate a new techno-economic sensitivity analysis. PI Martin-Ryals has carried out similar TEAs for novel wastewater treatment technologies including for algal wastewater treatment and membrane supported anaerobic wastewater treatment systems. The proposed TEA will take into consideration the quality and availability of wet-organic waste feedstocks specific to the Gainesville and Alachua County area. This will represent a relatively unique combination of feedstocks. The TEA will also consider various biogas and digestate utilization pathways, which will have a direct impact on the carbon intensity score and economics of the system. Altogether, the resulting TEA will further the local and scientific communities' understanding regarding energy recovery potential, economics, and potential operational risks and mitigation strategies for co-digestion of community wet-organic wastes.

IV. Benefits for End Users

This project will directly support the City of Gainesville's Zero Waste and No Net Emissions energy goals. Considering that the City of Gainesville and Alachua County currently spend energy and money to transport community FW to Raiford, Florida for landfilling, implementation of a local FW digester will reduce carbon emissions, generate renewable energy, and potentially reduce waste management costs for the local community.

To that aim, results from the proposed project will aid City and County stakeholders as they consider the feasibility of implementing a full-scale digester to manage local FW. The specific objectives for this project were established based on meetings with City and County officials, and are intended to compliment the DOE funded feasibility study that the City will carry-out. There are very few full-scale FW digesters in the U.S., and thus development in this area comes with uncertainty and potential risk. The findings from the proposed project will aid in understanding that uncertainty. Specially, the proposed project will evaluate potential risks and mitigation strategies associated with AD of FW and co-digestion substrates including FOG and wastewater biosolids, so that planners and operators are prepared to adjust accordingly.

The results and ML-framework developed through this project will be transferable to other AD projects, and will help to advance the application of AD for FW management at the state and national level. In addition to City and County representatives, the Technical Awareness Group (TAG) for this project will include representatives from an international digester company, Biagan A/S, and a national energy delivery company, Chesapeake Utilities. Both entities have interest in expanding AD of FW and renewal natural gas projects within the United States. Thus, insights generated from this project will be applicable to future projects implemented by these and similar industry entities.

V. Project Deliverables

Project deliverables will include the following:

- **Quarterly Progress Reports** to be submitted to the Hinkley Center and shared with TAG
- **Draft Final Technical Report** to be reviewed by TAG
- **Final Technical Report** to be submitted to Hinkley Center upon project completion
- **Presentation** of project findings at a relevant research/industry conference
- **Publication** of project results in a peer reviewed journal after completion of the project

Three official TAG meetings will be held over the 1-year project period. An initial kick-off meeting will be held at the start of the project to introduce TAG members, reorient everyone to the project goals and timeline, and address any initial concerns or project logistics. A second TAG meeting will be held at month 6 to provide an update on the project's progress. A final TAG meeting will be held at month 11 to summarize and review the project's results and provide feedback on the draft final report. Additional TAG meetings, or meetings with individual TAG members will be held as needed to address any issues or questions that may come up during the course of the project. All official TAG meetings will allow for remote participation via Zoom. A video recording and typed meeting minutes will be taken and made available via the project website.

A project website will be established prior to the start of the project, and will remain active for 18 months past the project's completion. The website will include a description of the project and the project team, as well as other useful information and resources related to AD of FW, sustainability, and resource recovery from wet-organic waste. The website will be updated with quarterly reports, TAG meeting minutes, videos of TAG meetings, and digital photographs of investigators and students engaged in activities related to the project.

During the course of project, likely in the last 2 months of the project, it is anticipated that the project findings will be presented as an oral presentation at a relevant research or industry conference/expo. This will be dependent on abstract acceptance by the conference. In addition, upon completion of the project, the research findings will be compiled into a manuscript for peer review and publication.

VI. Plan for Seeking Additional Funding

The objectives of the proposed project align with priorities of several external funding agencies including the U.S. DOE Bioenergy Technologies Office's (BETO) focus on "developing technologies that convert domestic biomass and other waste resources (e.g., municipal solid waste, biosolids) into low carbon biofuels and bioproducts," the USDA-NIFA AFRI aim of stimulating the bioeconomy, NSF's Environmental Engineering and Environmental Sustainability programs aimed at eliminated waste and enabling a circular bioeconomy, and NASA's need for regenerative biological life-support systems that can recycling water, carbon and nutrients to sustain humans during long duration space missions. As such, the PIs will leverage results from the proposed project to apply for additional external funding through these agencies. PI Martin-Ryals submitted an NSF Career proposal in July '22, which if awarded will directly support expansion of the proposed work. If not awarded, PI Martin-Ryals intends to update and resubmit that proposal.

PI Martin-Ryals' research program, which focuses on advancing organic waste utilization and circular bioeconomy solutions, is currently supported by DOE, USDA, and UF IFAS funding. PI Martin-Ryals has experience applying for and collaborating on DOE sponsored projects and was an invited speaker at the 2021 ACS Green Chemistry and Engineering Symposium, DOE BETO Bioprocessing Separations Consortium special session "Bioprocessing Separations: Advancing a Research Agenda". She has experience carrying out life-cycle assessment and technoeconomic analysis for waste treatment and biomass utilization process including a current a DOE sponsored project investigating algal wastewater treatment, and a USDA sponsored project on lithium-ion battery production. She has served as technical reviewer for the California Deptartment of Food and Agriculture Dairy Digester Research and Development Program, (2020 and 2022), and was a recent invited speaker at the Johnson Space Center to present on her experience with sustainable, closed-loop wet-organic waste treatment.

In addition to federal funding agencies, the TAG that has been assembled to support the proposed project includes representatives from the anaerobic digestion and renewable natural gas industries. It is anticipated the proposed project will lead to future collaborations and potential industry sponsorship for additional related projects and/or to further advance the technology developed through the proposed project.

VII. Detailed Budget *(removed for website)*

VII. Budget Justification *(removed for website)*

VIII. Scope of Work

The aim of this project is to evaluate the variability and uncertainty of AD of FW as a function of feedstock composition and operating parameters, and develop a machine learning (ML) based framework that can predict AD performance from feedstock composition and operating parameters. This will be achieved by carrying-out the following research objectives and tasks:

***Objective 1* – Establish a dataset linking feedstock characteristics, AD operating parameters, and AD performance metrics.**

Task 1: Literature Review for Data Collection: An extensive literature review will be carried out to establish a dataset linking feedstock characteristics (e.g., macro- and micro-nutrients, total solids, volatile solids, total carbon, total nitrogen, etc.) and operating parameters (e.g., organic loading rate, retention time, temperature, pH, etc.) to AD performance metrics (e.g., methane production and digestate quality). At the same time, any process upset or inhibition mechanisms documented in the literature will be noted. We will set an initial target to review a minimum of 40 papers in the first month of the project to establish an initial "trial" dataset. This will be used to test various ML-learning algorithms as described further in Task 3. Initial results from Task 3 will inform whether different kinds of data should be obtained from the literature, and additional rounds of literature review and model development will be carried out accordingly. We will set a target to review at least 200 papers to establish a comprehensive dataset. The review will focus on experimental studies that investigated AD of post-consumer FW (e.g., restaurant and residential FW). We will also review studies that investigated co-digestion of FW with FOG and/or wastewater biosolids. As time and resources permit, will may also review papers that investigated AD of FOG and wastewater biosolids separately.
Task 2: Literature Review for Potential Risks and Mitigation Strategies: A element of the literature review will be to further understand the potential process upsets and inhibition mechanisms that were noted in Task 1, and to identify potential mitigation strategies. In addition to the research papers reviewed in Task 1, a review of recent review papers that summarize mechanisms for potential process upsets/inhibition will be carried out to establish a complete inventory of potential operational risks and mitigation strategies. We will target a minimum of 10 review papers for this task.

The two literature review tasks will be carried out by the graduate student hired for this project, with assistance from an undergraduate OPS worker under the guidance of PI Martin-Ryals. We will use the UF library databases including Web of Science.

***Objective 2* – Develop a ML-framework to predict AD performance based on feedstock characteristics and operating parameters.**

Task 3: Develop ML Process Model: The data set established in Task 1 will be used to evaluate various ML algorithms/models to develop a framework for predicting AD performance (e.g., methane production and digestate characteristics) from feedstock characteristics and operating parameters. This task will be carried out by the graduate student hired for the project, under the guidance of Co-PI Bliznyuk who is an expert in Statistics and Machine Learning.

Specifically, we will evaluate existing approaches rooted in mechanistic models (ADM1) and use their performance as the baseline. We shall consequently investigate the prediction accuracy gains from data driven predictive modeling ML approaches (e.g., ANN), as well as from any hybrid approaches that will potentially combine the conventional mechanistic models with machine learning (e.g., using the outputs of mechanistic models as inputs for machine learning and/or via ensembles). These approaches will be used to identify the utility of different sources of data for reducing the prediction uncertainty and will help guide future data collection efforts (e.g., to emphasize the data sources that reduce uncertainty the most given the available budget). In addition to the ANN and deep learning approaches, we shall investigate statistical machine learning (SML) approaches that, in addition to point-level predictions, allow predictive uncertainty quantification. The ML model training and performance assessment will leverage K-fold cross-validation (CV), which allows one to control against potential overfitting. Specifically, each model will be trained repeatedly (K times) using (K-1) folds (disjoint data subsets) and assessed on the left-out validation subset to compute a predictive performance metric such as the mean squared (or absolute) error between predicted and observed outcome (e.g., methane output).

***Objective 3* – Sensitivity Analysis to evaluate potential impact on carbon intensity and cost.**

Task 4: Determine Carbon Intensity of FW AD System: The DOE established GREET model will be used to determine the carbon intensity (CI) score for AD of FW. The CA GREET 3.0 model is what is used by the California Air Resource Board (CARB) for establishing CI scores for various fuel pathways. Sensitivity analysis will be conducted on the CI score taking into consideration variation due to FW composition, operating parameters, co-digestion, biogas upgrading, and digestate utilization options, as relevant. The CI scores determined through this project's sensitivity analysis will be compared to the range of CI scores determined by CARB for fuels derived from AD of FW.

Task 5: Carry-out Techno-economic Sensitivity Analysis: The CI score determine in Task 4, will be used to evaluate the net present value of AD of FW, again taking into consideration variation due to FW composition, operating parameters, co-digestion, biogas upgrading, and digestate utilization options. In addition, potential tipping fee and transportation cost savings will be considered. The TEA will include CAPEX and OPEX values. CapdetWorks modeling software will be used to estimate costs, and foundational assumptions will be based on standard DOE assumptions such as a 10% IRR, financing of capital, depreciation based on a 7-year MACRS, etc.

These two tasks will be carried out by the graduate student hired for this project, under the guidance of PI Martin-Ryals.

IX. Technical Awareness Group

The Technical Awareness Group (TAG) for this project will include local sustainability and waste managers from the City of Gainesville and Alachua County as well as a planning engineer from Gainesville Regional Utility. In addition, the TAG will include representatives from industry and consulting including an international digester company (Søren Jørgensen, Bigadan), the biogas utilization industry (Justin Stankiewicz, Chesapeake Utilities), and an expert in land application of digestate (Del Bottcher, Soil and Water Engineering Technology). A list of the six TAG members and their contact information is provided in Table 2.

Table 1. Summary of TAG members with contact information

TAG Member	Title/Affiliation	Email/Telephone
Mike Heimbach	Sustainability Manager, Public Works Department – Solid Waste Division, City of Gainesville	HeimbachMJ@GainesvilleFL.gov (352) 393-7956
Eric Neihaus, P.E.	Planning Engineer, Gainesville Regional Utilities	NeihausEW@gru.com (352) 393-1742
Patrick Irby	Waste Collection & Alternatives Manager, Solid Waste and Resource Recovery, Alachua County	pirby@AlachuaCounty.US (352) 548-1285
Søren Jørgensen	Senior Vice President, Global Business Development, Bigadan A/S	sjj@bigadan.dk (650) 714-2650
Justin Stankiewicz	Director of RNG Development, Chesapeake Utilities Coporation	jstankiewicz@chpk.com (904) 451-8025
Del Bottcher, PhD, P.E.	Consulting Engineer and President of Soil and Water Engineering Technology, Inc.	dbottcher@swet.com (352) 281-2876
David Gregory	Manager, Solids Waste Division Orange County Utilities	david.gregory@ocfl.net (407) 254-9622
Timothy Townsend, PhD, P.E.	Professor, UF ESSIE, Executive Director, Hinkley Center for Solid and Hazardous Waste Management, Gainesville, FL	ttown@ufl.edu (352) 392-0846
Steven Laux, PhD, P.E.	Professor of Practice, UF ESSIE Hinkley Center for Solid and Hazardous Waste Management, Gainesville, FL	slaux@ufl.edu 352-871-7069

X. Project Timeline and Milestones

Project Objectives and Deliverables	2023					2024						
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Obj. 1. Literature Review												
Obj. 2. ML-model Develop												
Obj. 3. Sensitivity Analysis												
Finalize Project Reporting												
Establish Project Website	★											
TAG Meetings	**TAG**					**TAG**					**TAG**	
Quarterly Report Submission			**QR**			**QR**			**QR**			
Draft Report Complete											**Draft**	
Final Report Submission												**Final**
Conference Presentation												★

XI. Communicating Results with Stakeholders

Results from this project will be shared with the TAG members who will be able to distribute them to relevant stakeholders including City and County planners, policy makers, waste managers and waste treatment plant operators. PI Martin-Ryals will also be available to work with City and County officials to hold meetings and/or workshops as needed to share the results and information gained from this project with relevant stakeholders. All reports and products generated from this work will be available on the project website for at least 18 months after project completion. The scientific findings will be presented at at least one relevant research/industry conference such as the International Biomass Conference and Expo, the Air and Waste Management Association Conference and Expo, or the Water Environment Federation's Technical Exhibition and Conference. After completion of the project, the work will also be submitted as a manuscript for peer review publication.

XII. Documentation of Past Performance

Neither the PI nor Co-PI have received prior Hinkley Center funding.

References

1. Batstone, D., Keller, J., Angelidaki, I., Kalyuzhnyi, S., Pavlostathis, S., Rozzi, A., Sanders, W., Siegrist, H., Vavilin, V. (2002). Anaerobic digestion model No 1 (ADM1). *Water Science and Technology*. 45. 65-73.
2. Beltramo, T., Klocke, M., Hitzmann, B., (2019) Prediction of the biogas production using GA and ACO input features selection method for ANN model. Inf. Process. Agric. 6, 349–356.
3. Braguglia, Gallipoli, Gianico, Pagliaccia (2018) Anaerobic bioconversion of food waste into energy: a critical review. *Bioresour Technol*, 248, pp. 37-56, 10.1016/j.biortech.2017.06.145
4. Callaghan, F.J.; Wase, D.A.J.; Thayanithy, K.; Forster, C.F. (2002) Continuous co-digestion of cattle slurry with fruit and vegetable wastes and chicken manure. *Biomass Bioenergy*, 22, 71–77.
5. City of Gainesville (2022) Gainesville Zero Waste Initiative. https://www.gainesvillefl.gov/Government-Pages/Government/Departments/Public-Works/Garbage-Recycling/Zero-Waste-Initiative#section-2
6. Choi, Kim, Lee, Long-term monitoring of a thermal hydrolysis-anaerobic co-digestion plant treating high-strength organic wastes: Process performance and microbial community dynamics. *Bioresour. Technol*., 319 (2021),
7. Cruz, Chuenchart, Long, Surendra, Andrade, Bilal, Liu, Figueiredo, Khanal, Ferreira (2022) Application of machine learning in anaerobic digestion: *Perspectives and challenges, Bioresource Technol.*, Volume 345, ISSN 0960-8524
8. Dalke, Demro, Khalid, Wu, Urgun-Demirtas (2021) Current status of anaerobic digestion of food waste in the United States, *Renewable and Sustainable Energy Reviews*, Volume 151, ISSN 1364-0321
9. De Clercq, D., Wen, Z., Fei, F., Caicedo, L., Yuan, K., Shang, R. (2020) Interpretable machine learning for predicting biomethane production in industrial-scale anaerobic co-digestion. *Sci. Total Environ.* 712
10. Dong, C., Chen, J. (2019) Optimization of process parameters for anaerobic fermentation of corn stalk based on least squares support vector machine. *Bioresour. Technol.* 271, 174–181.
11. Elsamadony, Mostafa, Fujii, Tawfik, Pant (2021) Advances towards understanding long chain fatty acids-induced inhibition and overcoming strategies for efficient anaerobic digestion process. *Water Research*. 190,0043-1354, https://doi.org/10.1016/j.watres.2020.116732.
12. EPA. (2020). 2018 Wasted Food Report. Estimates of generation and management of wasted food in the United States in 2018. EPA 530-R-20-004. Office of Resource Conservation and Recovery.
13. EPA. (2023) Overview for Renewable Fuel Standard. https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard. Accessed 04/2023
14. FAO. (2011). Global food losses and food waste – Extent, causes and prevention. Rome
15. Filer, Ding, Chang (2019) Biochemical methane potential (BMP) assay method for anaerobic digestion research. *Water*, 11, p. 921, 10.3390/w11050921
16. Ghatak, M. Das, Ghatak, A. (2018) Artificial neural network model to predict behavior of biogas production curve from mixed lignocellulosic co-substrates. *Fuel* 232, 178–189.

17. Guo, H. nan, Wu, S. biao, Tian, Y. jie, Zhang, J., Liu, H. tao, (2021) Application of machine learning methods for the prediction of organic solid waste treatment and recycling processes: A review. *Bioresour. Technol.* 319, 124114.
18. Hagos, Zong, Li, Liu, Lu (2017) Anaerobic co-digestion process for biogas production: progress, challenges and perspectives. *Renew Sustain Energy Rev*, 76, pp. 1485-1496, 10.1016/j.rser.2016.11.184
19. Heo, N.H.; Park, S.C.; Kang, H. Effects of Mixture Ratio and Hydraulic Retention Time on Single-Stage Anaerobic Co-digestion of Food Waste and Waste Activated Sludge. *J. Environ. Sci. Health* Part A 2004, 39, 1739–1756.
20. Jossi (2021). California clean fuel standard sparks renewable gas boom in Midwest. Energy News Network
21. Karki, R., Chuenchart, W., Surendra, K.C., Shrestha, S., Raskin, L., Sung, S., Hashimoto, A., Kumar Khanal, S. (2021) Anaerobic co-digestion: Current status and perspectives. *Bioresour. Technol.* 330, 125001.
22. Khanal (2008) Anaerobic Biotechnology for Bioenergy Production: Principles and Applications Wiley- Blackwell, Ames, IA, USA
23. Kim, H.-W.; Han, S.-K.; Shin, H.-S. (2003) The optimisation of food waste addition as a co-substrate in anaerobic digestion of sewage sludge. *Waste Manag. Res.,* 21, 515–526.
24. Kirtikumar C. Badgujar, Bhalchandra M. Bhanage, (2018) Dedicated and Waste Feedstocks for Biorefinery: An Approach to Develop a Sustainable Society, *Waste Biorefinery*, 3-38
25. la Cour Jansen, J.; Gruvberger, C.; Hanner, N.; Aspegren, H.; Svärd, A. (2004) Digestion of sludge and organic waste in the sustainability concept for Malmö, Sweden. *Water Sci. Technol.,* 49, 163–169
26. Lamolinara, Perez-Martinez, Guardado-Yordi, Fiallos, Dieguez-Santana, Ruiz-Mercado (2022) Anaerobic digestate management, environmental impacts, and techno-economic challenges. *Waste Management.* 140 14-30 https://doi.org/10.1016/j.wasman.2021.12.035
27. Li, R.; Chen, S.; Li, X. (2009) Anaerobic Co-digestion of Kitchen Waste and Cattle Manure for Methane Production. *Energy Sour. Part Recovery Util. Environ. Eff.,* 31, 1848–1856.
28. Morales-Polo, C.; Cledera-Castro, M.D.M.; Moratilla Soria, B.Y. (2018) Reviewing the Anaerobic Digestion of Food Waste: From Waste Generation and Anaerobic Process to Its Perspectives. *Appl. Sci.*, *8*, 1804. https://doi.org/10.3390/app8101804
29. Neto, Ozorio, Campos de Abreu, Ferreira dos Santos, Pradelle (2021) Modeling of biogas production from food, fruits and vegetables wastes using artificial neural network (ANN) *Fuel*, 285 p. 119081
30. Paritosh, Kushwaha, Yadav, Pareek, Chawade, Vivekanand (2017) Food waste to energy: an overview of sustainable approaches for food waste management and nutrient recycling. *BioMed Res Int*, pp. 1-19, 10.1155/2017/2370927
31. Seo, K.W., Seo, J., Kim, K., Ji Lim, S., Chung, J. (2021) Prediction of biogas production rate from dry anaerobic digestion of food waste: Process-based approach vs. recurrent neural network black-box model. *Bioresour. Technol.* 341, 125829.
32. Senol, H. (2021) Methane yield prediction of ultrasonic pretreated sewage sludge by means of an artificial neural network. *Energy* 215, 119173.

33. Strik, Domnanovich, A.M., Zani, L., Braun, R., Holubar, P., (2005). Prediction of trace compounds in biogas from anaerobic digestion using the MATLAB Neural Network Toolbox. *Environ. Model. Softw.* 20, 803–810.
34. Wang, X., Bai, X., Li, Z., Zhou, X., Cheng, S., Sun, J., Liu, T., (2018). Evaluation of artificial neural network models for online monitoring of alkalinity in anaerobic co-digestion system. *Biochem. Eng. J.* 140, 85–92.
35. Xu, F., Li, Y., Ge, X., Yang, L., & Li, Y. (2018). Anaerobic digestion of food waste – Challenges and opportunities. *Bioresource Technology* (Vol. 247, pp. 1047–1058). Elsevier Ltd. https://doi.org/10.1016/j.biortech.2017.09.020
36. Zhang, L.; Lee, Y.-W.; Jahng, D. (2011) Anaerobic co-digestion of food waste and piggery wastewater: Focusing on the role of trace elements. *Bioresour. Technol.,* 102, 5048–5059.
37. Zhang, L., Loh, K.C., Lim, J.W., Zhang, J. (2019). Bioinformatics analysis of metagenomics data of biogas-producing microbial communities in anaerobic digesters: A review. *Renew. Sustain. Energy Rev.* 100, 110–126.
38. Zhang, C.; Xiao, G.; Peng, L.; Su, H.; Tan, T. (2013) The anaerobic co-digestion of food waste and cattle manure. *Bioresour. Technol.*, 129, 170–176.