Undergraduate Honors Thesis:
Simulating the Economic Feasibility of Anaerobic Digestion

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Abstract:

Ongoing research in major alternative energy sources has indicated that solar, wind and hydro energy are the most effective candidates to secure a greener future. However, due to the time and money it takes to develop this infrastructure, there is a gap in transitional energy sources which can slow climate change in the meantime. This study details the development of a model to predict the economic feasibility of an anaerobic digester. The goal of the model is to act as an accessible tool for other university campuses, farmers, organizations, and activists to gauge the viability of developing an anaerobic digestor in their area. The model consists of two main components: A simulation made in the chemical engineering software, Aspen Plus, and a supplemental web-based calculator that will refine the economic results outputted from the Aspen simulation and allow the public to access these results. Feedstock composition and flow rate were varied and trends in the responding economics of the process were observed to develop formulas that represent their relationship. The formulas were then incorporated into the second supplementary calculator component which also takes factors indirectly related to the anaerobic digestor into account, such as renewable energy credits, the price of electricity in the area, annual taxes, etc. As a product, it is expected that this project will become an easily accessible tool for users to determine if the construction of an anaerobic digester is right for their community.

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1. Introduction

The threat of climate change looms over the world and industry leads us closer and closer to surpassing the 1.5°C threshold. A threshold that, if passed, could lead to “severe climate disruptions that could exacerbate hunger, conflict, and drought worldwide” [1]. Now more than ever, efforts have been to minimize the usage of fossil fuels for energy, which is the main contributor to the greenhouse gasses that trap solar energy and warm the planet. Renewable energies such as solar panels, wind turbines, and hydroelectric dams are often what come to mind first when imagining how society can shift to alternative energy sources. However, the millennia-old technology of Anaerobic Digestion (AD) is an overlooked technology that can act as a supplemental renewable energy source, while also helping to combat the large amounts of annual global food wastage that could feed 2 billion additional people per year and 114.5 million metric tons of CO2 equivalent in annual methane emissions from landfills [2], [3].

Anaerobic digestion is the process by which organic waste is converted by microbes that thrive in oxygen-free environments, into the products of biogas and digestate. Digestate is often regarded as just a byproduct that can be used as fertilizer, animal bedding, or solid biofuel. The primary desired product is the methane component in biogas which can be combusted to produce thermal energy for personal purposes such as cooking, or on a more industrial scale for larger purposes such as electricity generation.

With such a large issue of food wastage and resulting emissions at stake, one cannot help but wonder why Anaerobic Digestion has not been pursued more urgently as a solution? The problem lies in the unpredictability of whether or not a biodigester will be successful until after it is already up and running [4]**.** The less that is known about the biodigester’s future feasibility in creating a profit, the less likely the biodigester will be adopted, even if it could very well be feasible. Studies have been conducted to relate digester failure to volatile fatty acid content, ammonia concentration, hydrogen concentration, and many other factors, where calculators have been made to model the preliminary economic feasibility of theoretical digester based on these relationships [5]–[7]. Yet they leave out important interactions such as reactor physics, and features such as feedstock customization, that not only challenge the usability of the calculator but the robustness of the underlying model itself [8].

A team of undergraduate students at UMass Amherst has designed the Undergraduates Raising Awareness for Anaerobic Digestion (URAAD) calculator that calculates economic feasibility for an Anaerobic Digester with emphasis on the externalities of AD such as electricity price, REC pricing, and tipping fees, allowing decision-makers to examine how the economic landscape impacts their proposed digester. Additionally, they performed sensitivity analyses to determine that O&M costs and feedstock processing had the largest impact on the Net Present Value. However, the problem lies in that the calculator as mentioned earlier, focuses on the externalities of the process so that anaerobic digestion of biogas and methane production depending on feedstock type and loading rate, which was deemed the most impactful aspect by the calculator's sensitivity analysis, is treated as a black box. Currently, the calculator has the user input volume amounts of wet biosolids (sewage) and source separated organic waste (compost and food waste). These feed volumes are then multiplied by factors taken from a consulting study by CDM Smith in 2013, to get the total biogas produced [9]. The CDM Smith study lacks a methodology and citations, urging skepticism about the validity of these factors. Additionally, this linear approximation leaves out any potential customization in the feedstock's composition and process operating conditions that could make the feasibility study more accurate to the user. In this study, I will be taking the opportunity to dive deeper into the effects of feedstock composition on the economic feasibility of anaerobic digestion, which will lead the URAAD calculator to become a more complete tool that can be better personalized to a user's individual case.

If I am able to conduct my own simulation, fitted models can then be developed from the simulation results for utilization in the URAAD calculator. This will allow universal access to a more encompassing calculator to determine if Anaerobic Digestion is economically feasible for their community. In contrast to other calculators, this new addition will allow the URAAD calculator to incorporate thermodynamics, reactor physics, and feedstock customization for a more accurate economic feasibility reading. Although there is a large amount of research on process modeling to optimize biogas productions, there is a lack of research on the economic modeling to optimize the economic success of an anaerobic digester, and so sensitivity analyses will be conducted on feedstock composition and loading rate to determine their effect on having an economically viable digester.

2. Literature Review

2.1 Anaerobic Digestion Background

Anaerobic Digestion is a set of biochemical reactions that occur in oxygen-deprived microbiomes where biological macromolecules present in food, agricultural, and sewage waste are fermented to produce biogas. The desired component in biogas is the methane which can be burned on its own for purposes such as cooking, or have its energy utilized to produce electricity for storage or application all while being safe if properly handled.

Normally, the waste that ends up in landfills is packed tightly enough to undergo anaerobic digestion anyway, to produce methane which then leaks into the atmosphere. Methane on its own has 80 times the global warming power than carbon dioxide does molecule per molecule, making it even more desirable for us to harness the methane as a power source, to minimize landfill emissions [10]. Additionally, the digestate left over in the digestion process is full of concentrated nitrogen which can be given to farms as fertilizer to further benefit the food supply.

The biochemical reaction network can be broken down into four main steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These steps run in chronological order in that the products of hydrolysis are reactants in acidogenesis and so forth. Each step is also carried out by its own unique set of microbes [11].

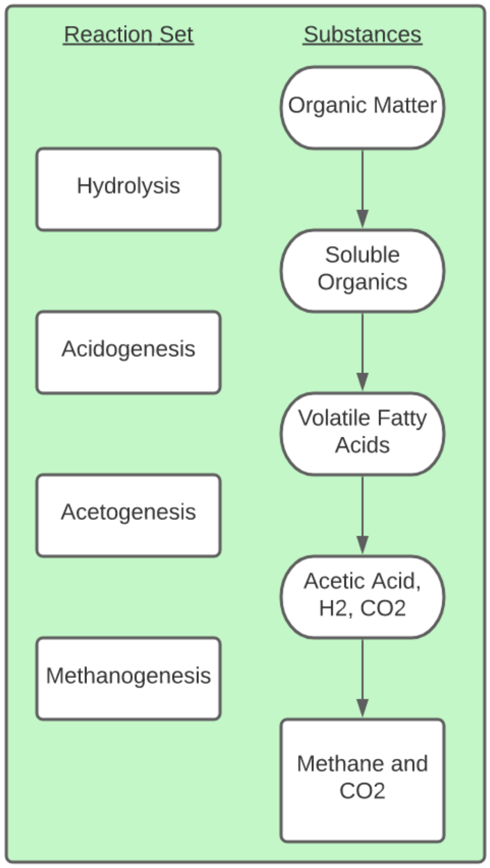

Figure 1. The main reaction system involved in anaerobic digestion.

Within hydrolysis, macromolecules (carbohydrates, proteins, lipids) are reacted with water to break them down into their simpler components (sugars, amino acids, fatty acids) while also producing hydrogen gas. Often the main goal is to reduce as many carbohydrates down as possible into simple sugars (fructose, glucose) that can be reacted once again in the acidogenesis stage with hydrogen gas.

In acidogenesis, the simpler molecules from hydrolysis are fermented with hydrogen gas to form organic acids. These acids are volatile fatty acids (VFA) whose presence strongly correlates with the amount of biogas produced.

In acetogenesis, the VFAs and remaining simple sugars are reacted with water to form hydrogen gas and carbon dioxide.

Finally, in methanogenesis, the VFAs, carbon dioxide, and hydrogen gas are consumed to produce out wanted methane along with water. In the methanogenesis step, the methanogens that carry out this reaction grow best in an anaerobic environment which characterizes the overall process as anaerobic [11].

2.2 Current Economic Analyses of Anaerobic Digestion

To determine whether a project is worth taking economically, the metric of Net Present Value (NPV) is often used. NPV takes into account the cash flows related to a project as well as the opportunity costs as a result of time passing. If the NPV is positive after the calculation, that means the project is worth undertaking and you get a net gain, whereas the magnitude thereon would show how much the net gain would be [12].

In [13], NPV is utilized to analyze the economic feasibility of operating and decommissioned anaerobic digesters. From the operating costs, capital expenses, and revenue streams, they were able to determine the correlation of feedstock content, size, and sellable products on the profitability of the digesters [13].

As a result, NPV will also be used in my simulation as the ultimate metric determining economic feasibility, using this paper as a guideline for its implementation in anaerobic digestion.

2.3 Mathematical Modeling

Before creating a simulation, it is first necessary to develop the underlying mathematical models that lead our input to a realistic result. A model commonly hailed as the most complete in Anaerobic Digestion is the International Water Association's Anaerobic Digestion Model No.1 (ADM1) [13]. It is highly cited in many AD simulation papers and provides the foundations by which we can begin to develop our simulations.

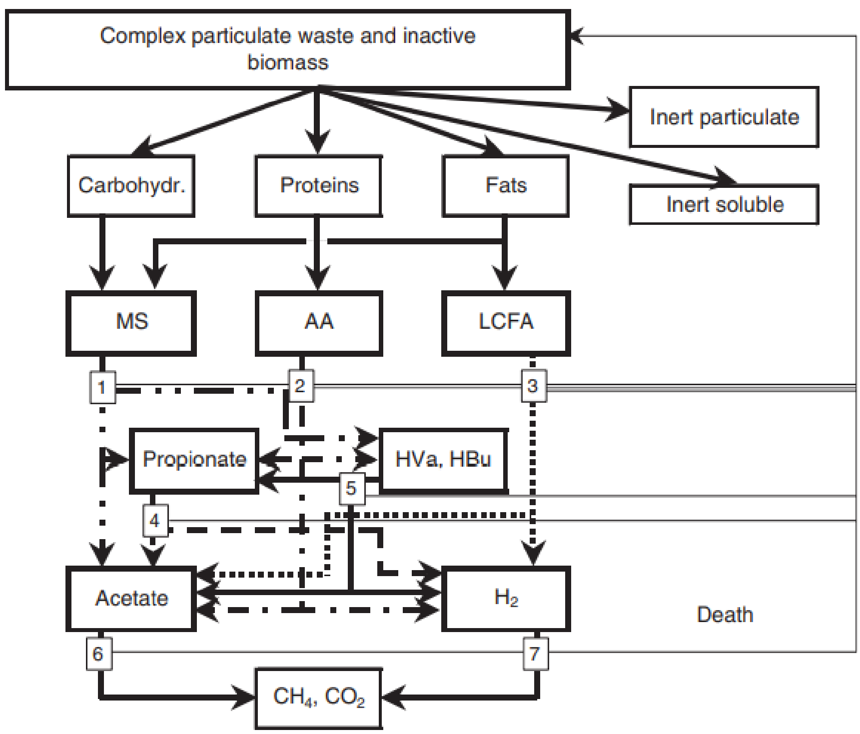

Figure 2. The network of biochemical reactions and their relationship utilized in ADM1.

Source: [13]

In one half of the model, it details the biochemical reactions. These are the reactions that rely on microbes to take up the reactants as substrate to then convert them to a product that can be used in a later step of the process. The particular event of substrate uptake is modeled by the Monod equation shown below:

$$\mu = (\frac{\mu_{max} S}{K_s + S})(\frac{K_i}{K_i + S})$$

Figure 3. Model for specific growth rate of microbes. **Source:** [14]

Where μ is the specific growth rate, μmax is the maximum achievable value of μ, S is the substrate concentration, Ks and is the saturation constant. The left factor models how the microbes grow based on substrate available while the right factor models the inhibition of growth based on the excess of substrate. This general equation can be implemented in determining biological product mass balances, providing more equations that will further complete the algebraic system. Inhibition responses of all microbes to pH, acetogenic microbes to hydrogen, and acetoclastic methanogenic microbes to free ammonia were also taken into account in the form of inhibition functions, so that the pH, hydrogen, and free ammonia factors impact the growth of the microbes in the model. All biochemical differential equations are detailed in Tables A.3 and A.4 of the paper's appendix for each component [13].

Additionally, the ADM1 models the physico-chemical processes, which are primarily the reactions that do not involve microbes and include liquid-liquid reactions, gas-liquid exchanges, and liquid-solid transformations where their components contribute to the inhibition of the biochemical processes' rates. The physico-chemical process gives better insights into gas solubility and pH which are involved in the microbial reactions.

More rigorous modeling has also been conducted for the solid phase of the anaerobic digestion process and its interaction with gas and liquid phases which could prove useful in developing more accurate simulations. However, with a lack of experimental data to test them, we will instead rely on the liquid state ADM1. As solid feedstock is normally watered to form slurries in digesters, ADM1 will be a sufficient model for our intents and purposes due to its global recognition [14].

2.4 Existing Simulations

As alluded to before, the ADM1 mathematical model operates as the underlying framework for many anaerobic digestion simulations. However, although ADM1 is considered complete in terms of kinetics calculations, it lacks the process's dependence on thermodynamics and reactor physics where many simulations have compensated for this by integrating ADM1 with the Aspen Plus simulation software [15]–[18]. With Aspen Plus's purpose of being used in the chemical engineering field, it contains the thermodynamics and reactor physics aspects that make up for the ADM1's faults. For example, when talking about reactor physics, the rate at which the organic feedstock is loaded into the reactor (Organic Loading Rate) and the resulting amount of time that each particle spends in the reactor on average (Residence Time) both impact biogas production and composition. According to research, there is a "sweet spot" for both of these factors to optimize reaction rate and selectivity [19]. Additionally, it is important to incorporate thermodynamics into our model as this determines the maximum conversion of our feedstock to biogas at any given condition. With the newly completed Aspen simulation in [15], computational sensitivity analyses were conducted for organic loading rate (OLR), hydraulic residence time (HRT), C/N ratio, fatty acid composition, ammonia content, feed rate, pH, and pressure, to then observe their effects on biogas production and composition. Afterward, these values were tested against experimental and historical data of lab scale and commercial anaerobic digesters. The simulations' results were within ~10% of the experimental results, suggesting it to be sufficient for our purposes of examining economic feasibility.

The model from [15] will be adopted and adapted as it directly translates formulas from the highly recognized ADM1 model seamlessly into Aspen using FORTRAN rather than attempting to translate to Aspen Plus's native inputs.

3. Methods

3.1 Aspen Simulation Setup

Simulations were carried out using Aspen Plus, a chemical engineering software that is considered industrially standard for process design. The model itself was taken from [15].

It uses the Anaerobic Digestion Model No. 1 (ADM1) math model as a basis for its kinetics calculations. The ADM1 model as mentioned before breaks down the process of Anaerobic Digestion into two interacting systems: (1) the biochemical reactions which encompass the conversion of compounds caused by bacteria and (2) the physico-chemical reactions which encompass all other related reactions. Kinetic rate equations are fully detailed for all reactions which allow the determination of the rate of reaction conversion for a given time.

The Rajendran simulation itself is broken down into the following simulation units: (1) a stoichiometric reactor that houses hydrolysis, (2) a continuously stirred reactor (CSTR) that houses acidogenic, acetogenic, and methanogenic reactions, and (3) FORTRAN program blocks that interact with both reactors, and calculates the degree of conversion of carbohydrates, proteins and fats, taking into account pH, growth rate of microorganisms, and ammonia inhibitions.

3.2 Undergraduates Raising Awareness for Anaerobic Digestion (URAAD) Calculator

The URAAD calculator is an anaerobic digester economic feasibility calculator built by a team of undergraduate students at UMass Amherst in 2020. As mentioned in the literature review, the calculator focuses more on the externalities of anaerobic digestion like electricity prices, Renewable Energy Credit (REC) prices, and tipping fees, rather than inputs or outputs of the process itself. The modeling of the anaerobic digestion process is much more simplified, where biogas production is determined through volume inputs from two general feedstock groups (wet biosolids and source separated organics) multiplied by a single factor taken from a 2013 study by CDM Smith [9]. Anaerobic digestion, as evident by the work that goes into its modeling in the ADM1 paper, is a much more complex process. The URAAD calculator was used as a base, to be then upgraded with empirical models generated from the Aspen simulations. All conditional formulas were coded in JavaScript and HTML.

3.3 Feedstock Composition and Simulation Validation

In order to input the chosen feedstocks of cow manure, pig manure, and food waste into the simulation, they had to be broken down into their simple components that Aspen Plus could understand. According to the [15]**,** the most important components to input were dextrose, proteins, lipids, hemicellulose, cellulose, and inert material present in the feedstock by mass composition to produce a realistic result for biogas production and methane composition. The cow manure and pig manure compositions were taken directly from the [15]'s citations [20], [21]. Food waste on the other hand was not directly cited by the Rajendran paper and was taken from the university-sourced food waste composition of the Lopez group [22]. The compositions can be seen in Table 1.

Table 1: Feedstock Types and their Compositions used in the Simulation

Feedstock Type	Dextrose	Proteins	Lipids	Inert	Hemicellulose	Cellulose
Pig Manure	0.0414	0.23	0.049	0.2804	0.1922	0.207
Cow Manure	0.2912	0.14	0.06	0.19	0.1526	0.1662
Food Waste	0.652	0.061	0.046	0.149	0.013	0.033

To confirm that these compositions were good representations of their feedstocks, the compositions were inputted into the simulation and the simulation's biogas production result was compared to those of the experimental result found in [15]'s validation cases. For cow manure, the simulation came to a 5.5% error in experimental results while for pig manure [23]**,** the simulation came out to a 3.0% error of experimental results[24]**.** Food waste unfortunately was not able to be validated, mostly due to the many variations in its composition depending on its sourcing. In the future, an anaerobic digestion experiment with food waste of known composition would be advisable to validate the simulation results for completeness.

3.4 Hydraulic Retention Time (HRT) and Total Solids (TS) %

The hydraulic retention time (HRT), also known as residence time, is a measure of the average amount of time that a substance spends in the system [25]. In this case, HRT is a measure of the average time that the feedstock spends in the biodigester. In the sensitivity analysis shown in Figure 4, it was found that biogas production and methane mass composition scales logarithmically with increasing HRT. As a result, HRT cannot be optimized by maximum productivity as biogas production and methane mass composition scale infinitely, though with diminishing returns. For the scenario simulations, an HRT of 21 days was assumed due to the frequency of its use in the validation samples of [15].

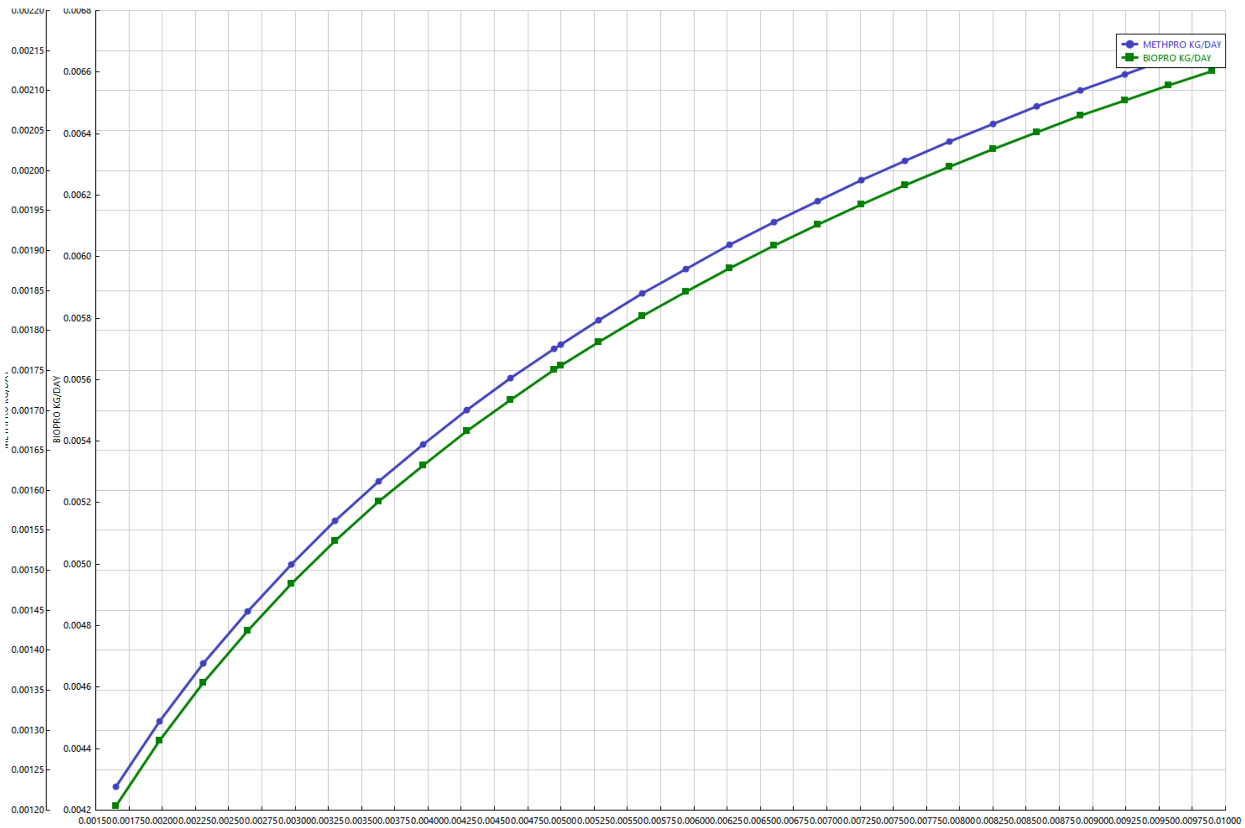

Figure 4. Sensitivity analysis depicting relationship between hydraulic retention time on the x axis, and methane production (Blue) and biogas production (Green) on the y-axis.

The total solids % is a measurement of the proportion of the feedstock volume that is dissolved or suspended solid [26]. For example, if a feed is 20% total solids that means it is 20% solid in volume and 80% liquid in volume. Typically, in the context of anaerobic digestion, the 20% solid will be made up of volatile solids which can be digested along with inert solids which are not converted in the digestion process. The 80% liquid on the other hand will be mostly comprised of water. For the same reason that the HRT was assumed to be 21 days, the total solids % was assumed to be 10% for all scenario simulations.

Total solids %, like HRT, was kept fixed at 10% due to the frequency of its use in the validation samples of [15].

3.5 Methane Mass Composition % Selection

From a preliminary simulation, it was found that methane mass composition slightly drops with increasing feedstock volumetric loading rate, resembling a negative logarithmic that can be seen in Figure 5. Since the composition quickly reaches an asymptote at very low loading rates, it was assumed that due to industrial anaerobic digestion typically occurring on larger scales, the methane composition for a feedstock could be taken as a constant equal to the methane composition at a high loading rate.

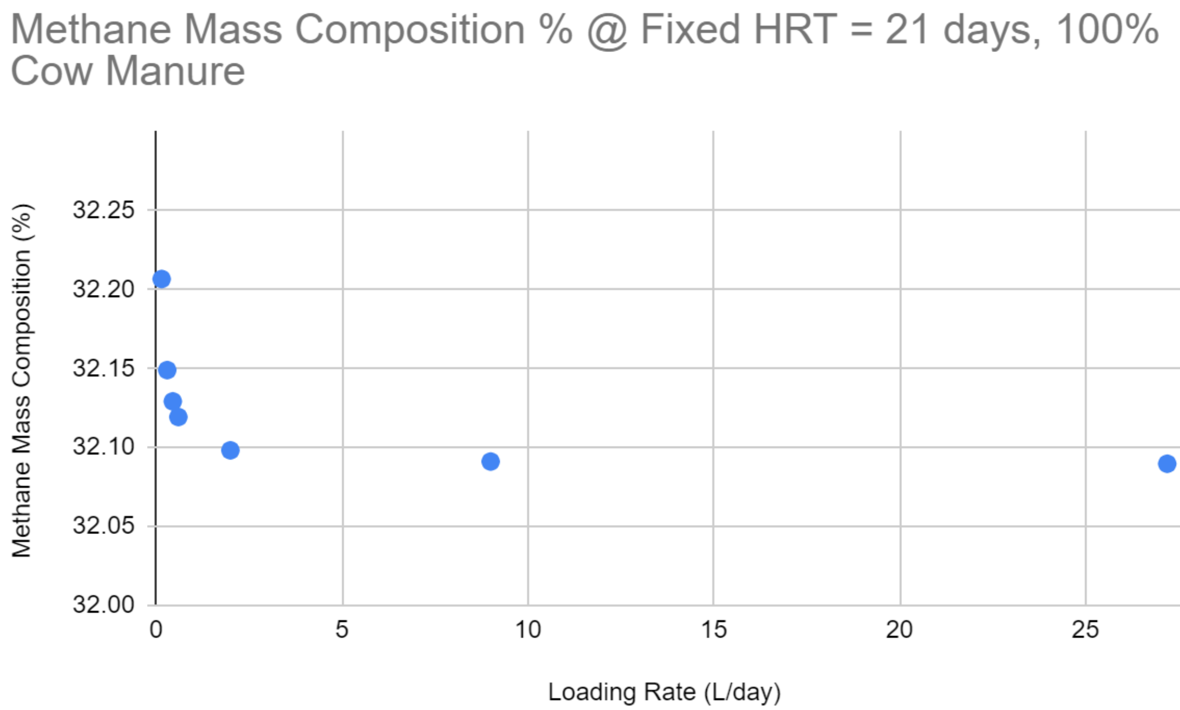

Figure 5. Graph depicting the effect of increasing loading rate on the methane mass composition of the biogas outputted.

3.6 Capital Cost Derivation

The capital cost is the one-time expenditure at the start of a project to purchase and install all the needed equipment and infrastructure. In the case of anaerobic digestion, this is the purchase and installation of the anaerobic digester and its associated modules like piping. In the URAAD calculator, the capital cost was taken as manual input from the user, but if the intended user is a person without much knowledge of anaerobic digestion, it seems unlikely that an accurate capital cost will be inputted. With the improvement of the URAAD, I considered this to be a good opportunity to make the capital cost automated.

The anaerobic digester is an open, agitated tank and so its costing by size can be found in the textbook “Chemical Engineering Economics” by Donald E. Garrett [27]. If the volume of the reactor is known, its cost can be determined by the following formula:

$$cost\ size\ 2 = cost\ size\ 1 (\frac{size\ 2}{size\ 1})^{size\ exponent}$$

The textbook gives the size exponent as 0.53, where size and the cost of size 1 were chosen to be 90 gallons and $3,000 respectively. Converting gallons to liters, we get:

$$cost\ size\ 2 = 3000 * (\frac{size\ 2}{3.785 * 90})^{0.53}$$

In order to account for the purchase of additional modules and the system’s installation, we must then multiply by the module factor and the installation factor which are given as 2.5 and 1.58 respectively.

$$Installed\ Cost = 3000 * (\frac{size\ 2}{3.785 * 90})^{0.53} * (1.58 + 2.5)$$

Finally, since the cost of agitated tanks in the textbook is relative to the time of its publishing in 1987, the changing economic landscape must be taken into account. This can be done by multiplying the installed module cost by the ratio of the Chemical Engineering indices from 1987 and the most recent one from 2021. These numbers come out to 320 and 777 [28].

$$Current\ Installed\ Cost = (3000 * (\frac{size\ 2}{3.785 * 90})^{0.53} * (1.58 + 2.5)) * \frac{777}{320}$$

This allows the calculation of the capital cost of the anaerobic digester depending on its reactor volume seen in Figure 6**.**

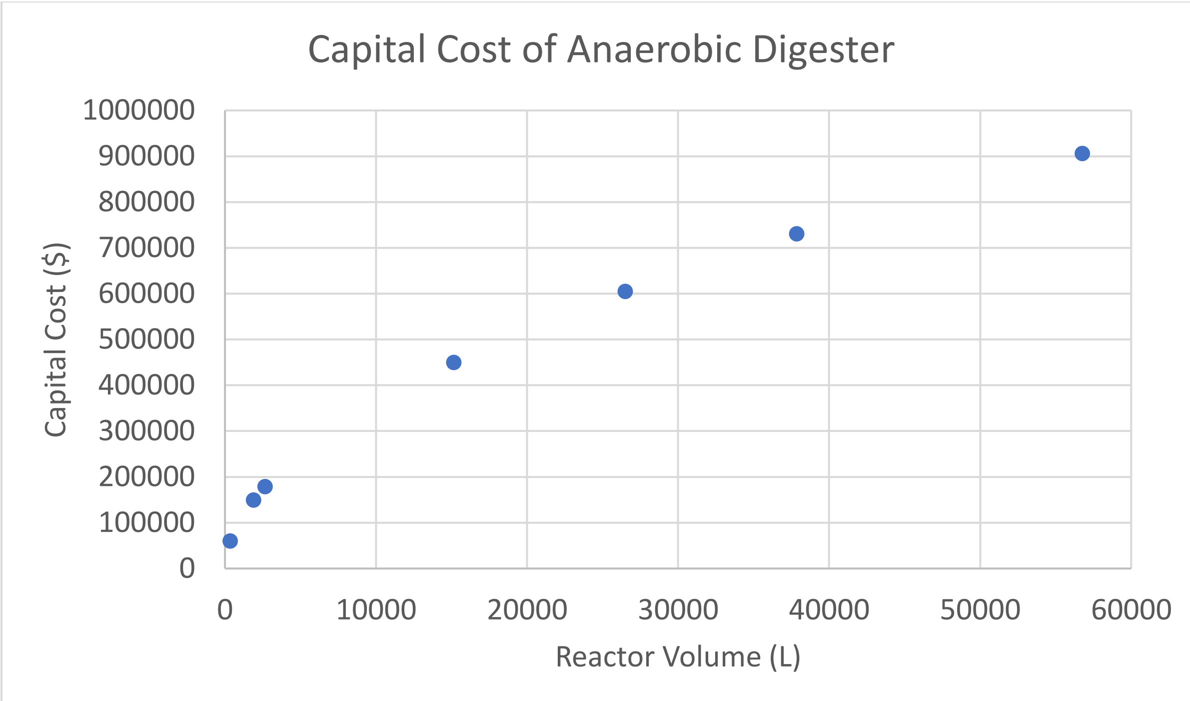

Figure 6. Graph depicting the capital cost of the anaerobic digester relative to the reactor volume.

3.7 Aspen Input and Excel Scenario Table

Feedstock scenarios were created for all binary combinations of pig manure, cow manure, and food waste in 20% mass composition intervals for a total of 6 data points per binary mixture. The composition was determined in the binary mixtures by multiplying each pure feedstock's components by their mass % compositions before summing them together.

Each scenario, shown in Figure 7, was then run through the Aspen Plus simulation, which then outputted biogas flow rate and methane mass composition %.

Feedstock Composition & Loading Rate Effect on Biogas Production and Methane Composition (HRT = 21 days & 10% TS)																	
		Input												Output			
Scenario	Active	Feed Loading Rate	Reactor Volume	Water Composition	Dextrose Composition	Ammonia Composition	Cellulose Composition	Hemicellulose Composition	Triolein Composition	Tripalm Composition	Protein Composition	Acetate Composition	Keratin Composition	Biogas Flowrate	Methane Mass Composition %	Status	
		l/day	l											kg/day			
Case 1	*	27.20	571.20	9.00	0.46	0.02	0.17	0.15	0.03	0.03	0.14	0.00	0.00	0.78	0.26	Results Available	Cow
Case 2	*	27.20	571.20	9.00	0.42	0.02	0.17	0.16	0.03	0.03	0.16	0.00	0.01	0.73	0.26	Results Available	20
Case 3	*	27.20	571.20	9.00	0.39	0.01	0.18	0.17	0.03	0.03	0.18	0.00	0.02	0.68	0.26	Results Available	40
Case 4	*	27.20	571.20	9.00	0.35	0.01	0.19	0.18	0.03	0.03	0.19	0.00	0.03	0.64	0.26	Results Available	60
Case 5	*	27.20	571.20	9.00	0.31	0.00	0.20	0.18	0.03	0.03	0.21	0.00	0.04	0.61	0.26	Results Available	80
Case 6	*	27.20	571.20	9.00	0.27	0.00	0.21	0.19	0.03	0.03	0.23	0.00	0.05	0.59	0.25	Results Available	Pig
Case 7	*	27.20	571.20	9.00	0.36	0.00	0.17	0.16	0.02	0.02	0.20	0.00	0.07	0.49	0.26	Results Available	20
Case 8	*	27.20	571.20	9.00	0.44	0.00	0.14	0.12	0.02	0.02	0.16	0.00	0.09	0.42	0.26	Results Available	40
Case 9	*	27.20	571.20	9.00	0.53	0.00	0.10	0.08	0.02	0.02	0.13	0.00	0.11	0.37	0.26	Results Available	60
Case 10	*	27.20	571.20	9.00	0.61	0.00	0.07	0.05	0.02	0.02	0.09	0.00	0.13	0.33	0.26	Results Available	80
Case 11	*	27.20	571.20	9.00	0.70	0.00	0.03	0.01	0.02	0.02	0.06	0.00	0.15	0.29	0.26	Results Available	Food Waste
Case 12	*	27.20	571.20	9.00	0.65	0.00	0.06	0.04	0.02	0.02	0.08	0.00	0.12	0.33	0.26	Results Available	20
Case 13	*	27.20	571.20	9.00	0.60	0.01	0.09	0.07	0.03	0.03	0.09	0.00	0.09	0.38	0.26	Results Available	40
Case 14	*	27.20	571.20	9.00	0.56	0.01	0.11	0.10	0.03	0.03	0.11	0.00	0.06	0.45	0.27	Results Available	60
Case 15	*	27.20	571.20	9.00	0.51	0.02	0.14	0.12	0.03	0.03	0.12	0.00	0.03	0.56	0.27	Results Available	80

Figure 7. Scenario table in Excel which shows all inputs (Blue) and outputs (Orange) of the simulation for every case tested.

4. Results and Discussion

4.1 Cow Manure and Pig Manure

In the binary mixture of cow and pig manure, shown in Figure 8, simulation data was generated for composition intervals of 20% of pig manure for a total of 6 points. The mass of biogas per volume of feedstock inputted was examined specifically, and it was found that with an increasing composition of pig manure, the slope of biogas production decreased in a quadratic fashion. The slope was fitted to the equation $y = 0.0039x^2 – 0.011x + 0.0288$ where x is the composition % of pig manure and y is the kg of biogas produced per L of feedstock. The fitted model was a great representation of the slope's behavior with varying compositions at an R^2 of 0.9996. There was a 25% change in slope from a full composition of cow manure to a full composition of pig manure, so it can be considered sensitive to this binary mixture's composition.

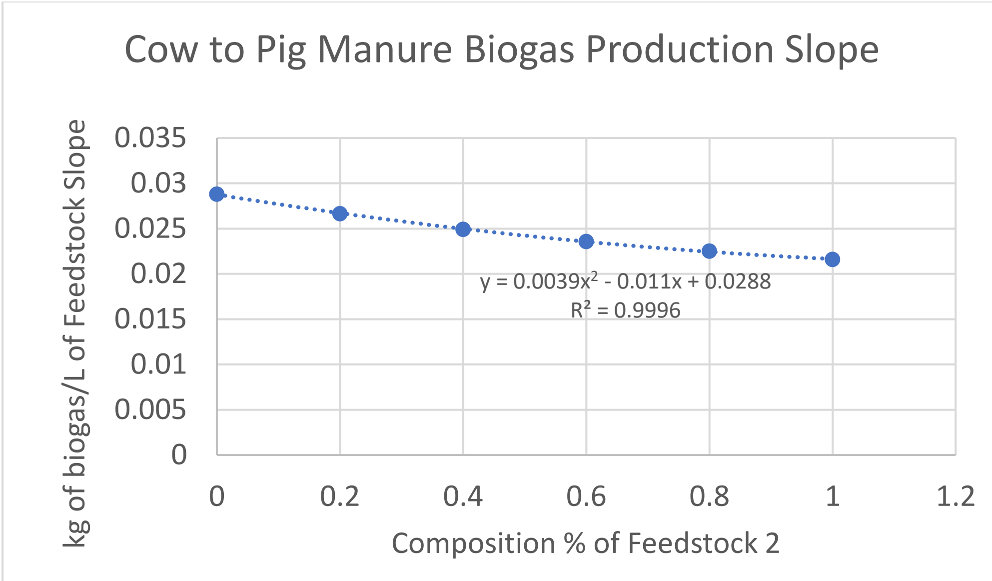

Figure 8. Graph depicting kilograms of biogas produced per liter of feedstock for different compositions of the cow manure and pig manure binary mixture.

The methane composition, for the same data set, followed a linear downtrend with the fitted model being y = -0.0099x + 0.2647, shown in Figure 9. In this case, x is the composition % of pig manure once again, but y is the methane mass composition % of the biogas. The model fitting was a perfect representation of the simulation data with an R^2 of 1. As there is only a 4% change from cow manure to pig manure composition, the methane composition can be deemed not sensitive to the composition of this binary mixture. With both biogas production slope and methane composition decreasing with the increase in pig manure composition, it is clear that pure cow manure feedstock is the all-around best feedstock to maximize methane production compared to pig manure.

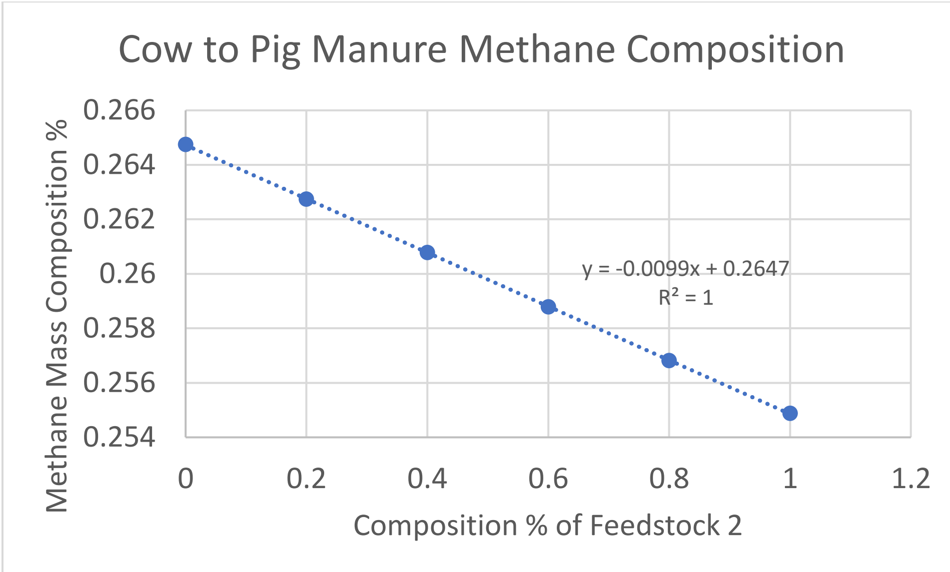

Figure 9. Graph depicting the methane mass composition % of the outputted biogas for different compositions of the cow manure and pig manure binary mixture.

4.2 Pig Manure and Food Waste

In the binary mixture of pig manure and food waste, a decrease in biogas production can be observed with an increase in food waste composition, as seen in Figure 10. Like the cow to pig manure mixture, an empirical model was cleanly fitted to a quadratic equation y = 0.0066x^2 - 0.0173x + 0.0215 with an R^2 of 0.9987. With a change of 50% in slope from pig manure to food waste, the slope can be considered very sensitive relative to the composition in the binary mixture.

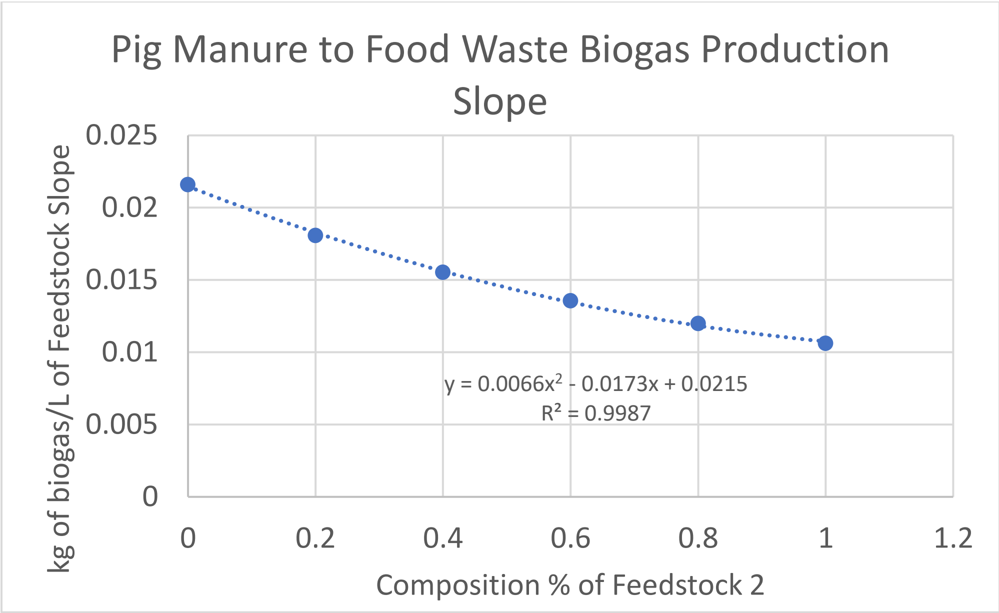

Figure 10. Graph depicting kilograms of biogas produced per liter of feedstock for different compositions of the pig manure and food waste binary mixture.

The methane mass composition % for the binary mixture of pig manure and food waste exhibited a cubic behavior with a slow methane mass composition % increase as food waste composition was increased, until the peak where there was a steeper decrease in methane mass composition %, as seen in Figure 11. The data was fitted with the cubic equation y = -0.0051x^3 – 0.0009x^2 + 0.008 + 0.2549 and an R^2 of 0.9974 suggesting a good fit. Since the methane composition only changed by 1% at most with varying compositions, the methane composition can be considered not sensitive to feedstock composition in this binary mixture.

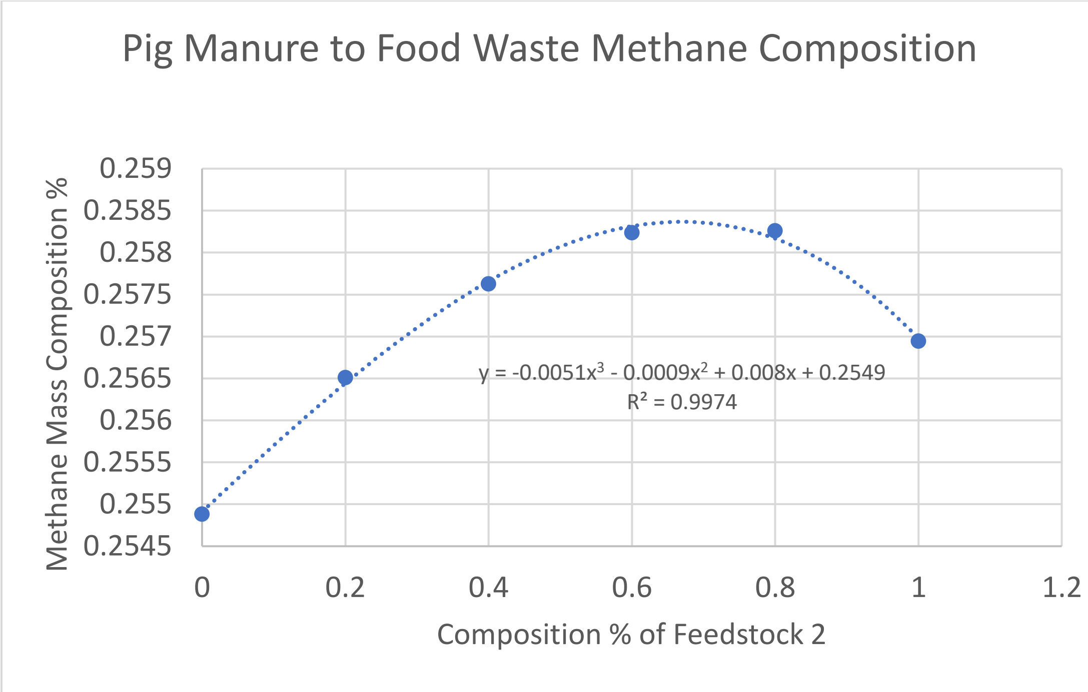

Figure 11. Graph depicting the methane mass composition % of the outputted biogas for different compositions of the pig manure and food waste binary mixture.

4.3 Cow Manure and Food Waste

The binary mixture of cow manure and food waste exhibited a decreasing quadratic behavior like the mixture of cow and pig manure, seen in Figure 12. The slope steeply fell as food waste was introduced into the mixture, but then began to level out towards the end. Its relationship can be modeled by the quadratic equation y = 0.0195x^2 – 0.0365x + 0.0281 with an R^2 of 0.9878 which is a slightly worse fit than the other models so far. With a slope change of 63%, the biogas product can be considered very sensitive relative to composition in the binary mixture.

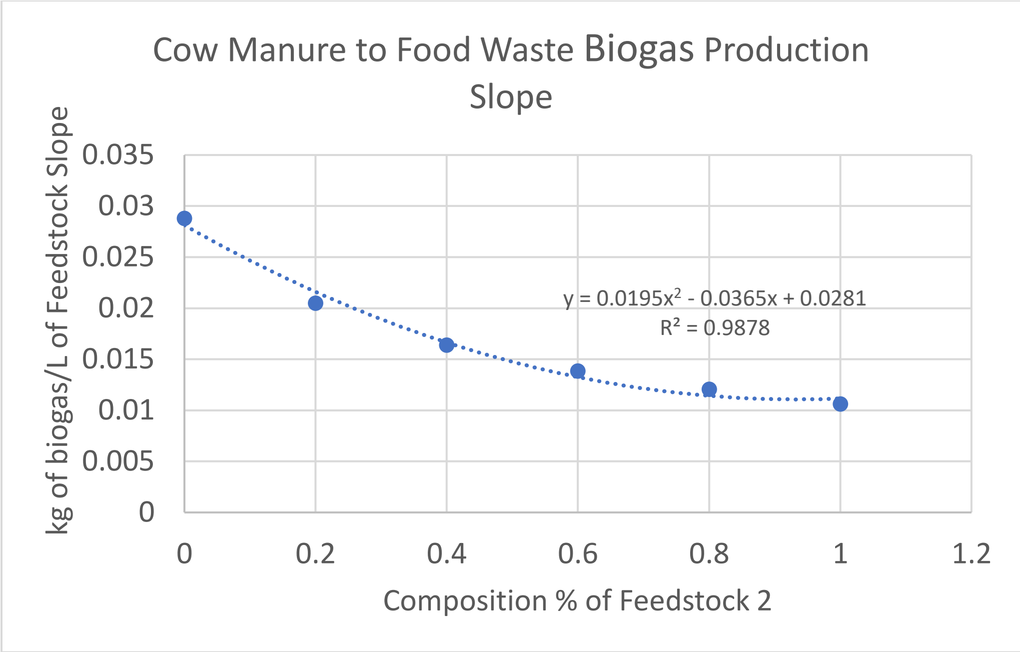

Figure 12. Graph depicting kilograms of biogas produced per liter of feedstock for different compositions of the cow manure and food waste binary mixture.

Methane composition for this same binary mixture exhibited a cubic behavior with a sharp increase in methane mass composition with increasing food waste composition, followed by a slow decrease in methane mass composition as food waste composition continues to increase. As seen in Figure 13, the mass composition was modeled with the cubic equation $y = 0.0083x^3 – 0.0299x^2 + 0.0138x + 0.2648$ which was a good fit, having an R^2 of 0.9981. With a maximum change of 4% relative to the composition of the binary mixture, the methane composition can be considered not sensitive.

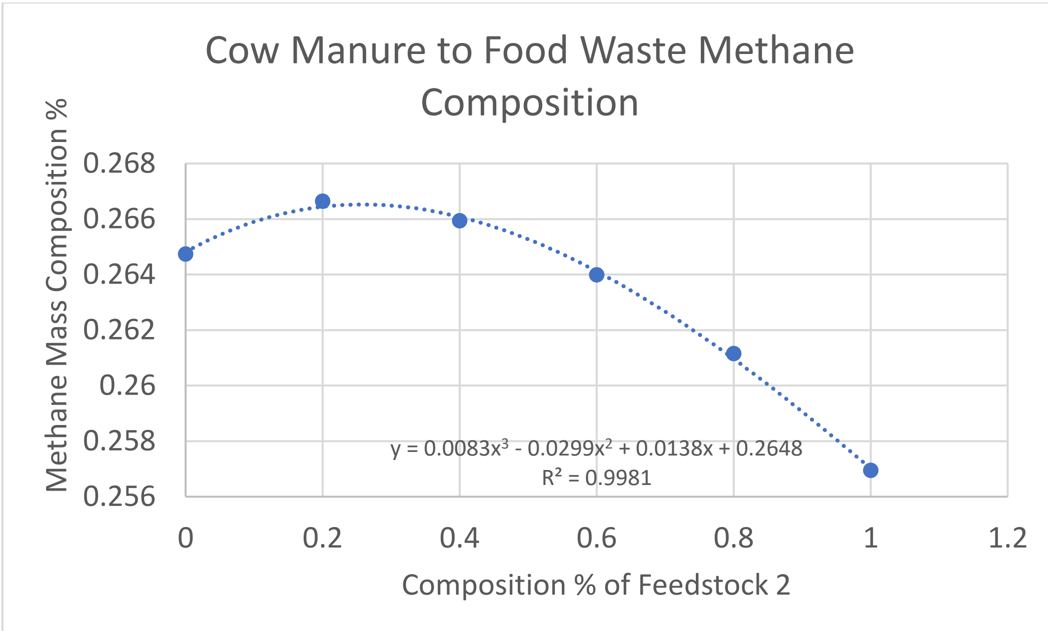

Figure 13. Graph depicting the methane mass composition % of the outputted biogas for different compositions of the cow manure and food waste binary mixture.

4.4 URAAD Website Development

The URAAD website was modified to incorporate the empirical models that were derived in the above sections. As seen in Figure 14, a dropdown list has been added that now allows users to select cow manure, pig manure, and food waste or any binary combination of them as feedstocks. Next, the user is allowed to type in a value that describes how much of the mixture is made up of the first mentioned feedstock and then the loading rate and the number of operating days. Capital cost, which was once a manual input, has now been removed as it is now automatically calculated as described in Section 3.6.

There is still room for improvement for the fields of Total O&M Costs, Annual Town Taxes, and Working Capital. It is unlikely that the user will know these parameters if they are using the calculator in the first place. For future direction, research should be done to automate their calculation with changing reactor volume as well as they are not as simple as a linear scaling.

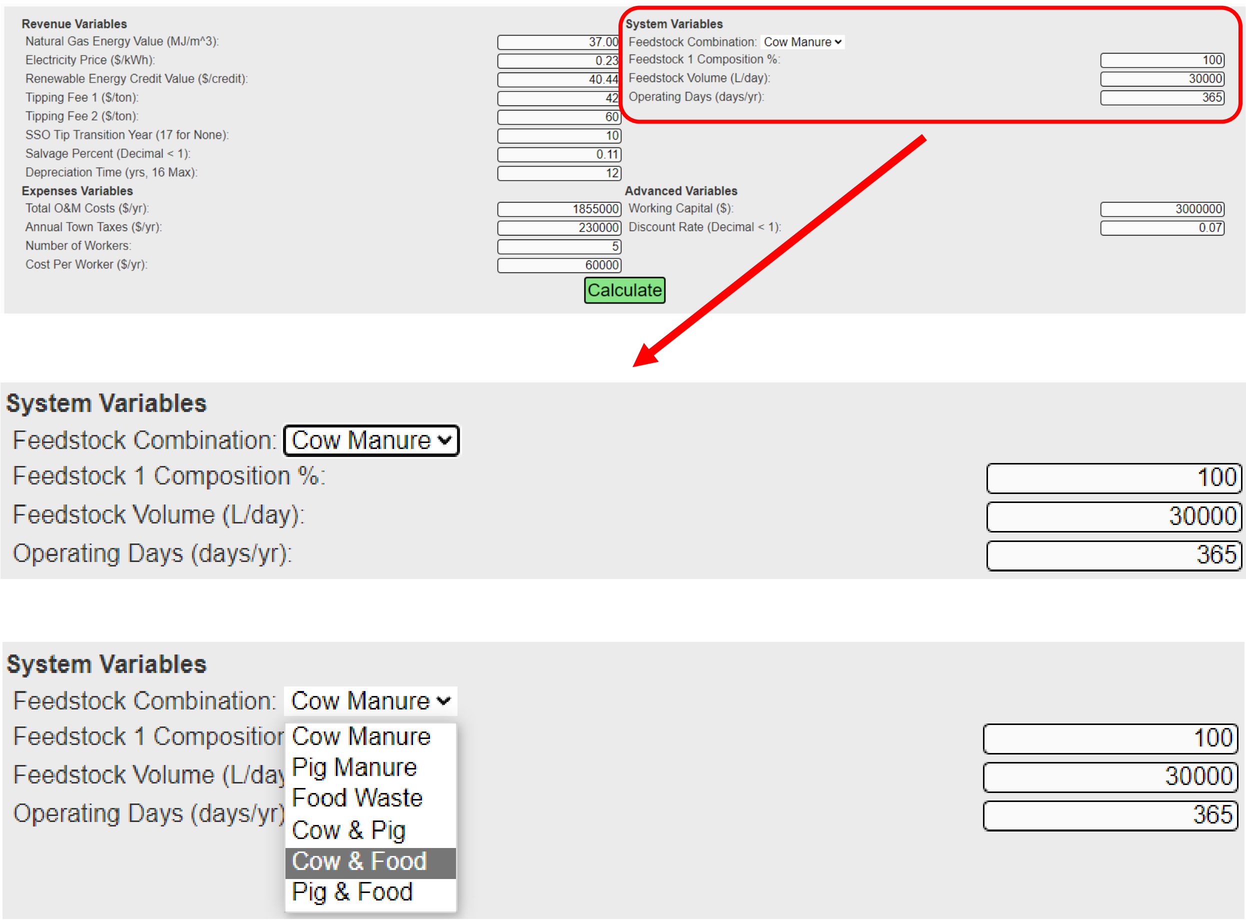

Figure 14. The new feedstock selection interface made for the URAAD calculator website.

4.5 Economic Feasibility Analysis

To compare the different feedstocks and their economic feasibility, a base case had to first be established so that O&M costs, Annual Town Taxes, and Working Capital could be kept fixed and accurate to reality. The base case was taken from [9] where 50,023 gallons of feedstock were loaded per day with O&M costs of 1,855,000 $/year, Annual Town Taxes of

230,000 $/year, and a Working Capital of $3,000,000. Composition intervals of 25% were inputted into the calculator yielding Figure 15.

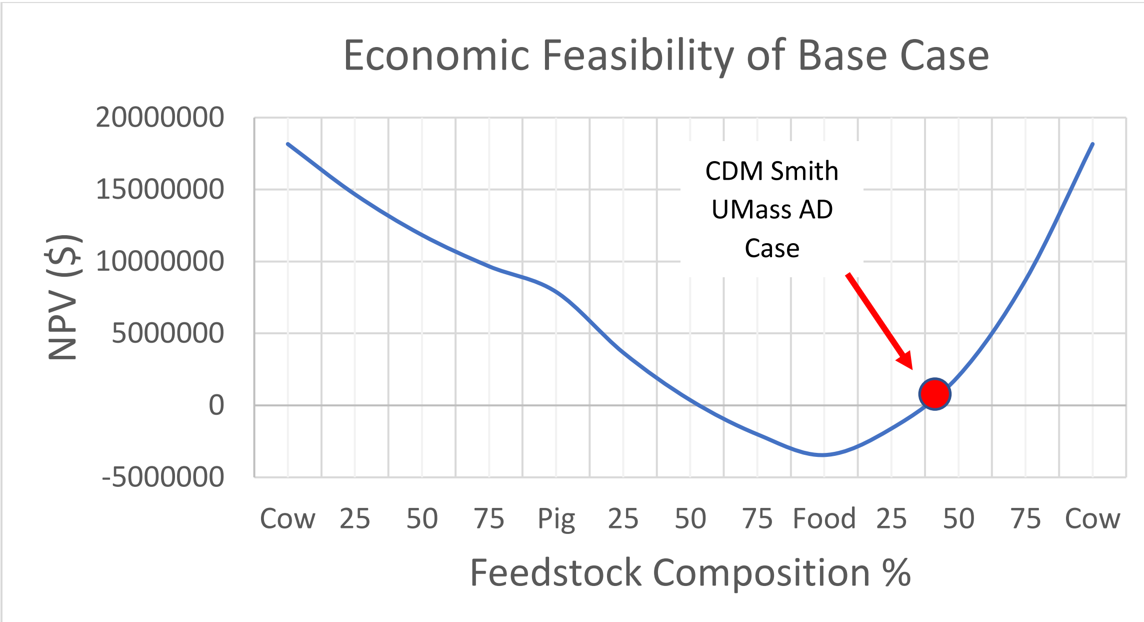

Figure 15. Graph depicting the Net Present Value of the CDM Smith base case when feedstock composition is varied between combinations of cow manure, pig manure, and food waste.

With a 50,023 gal/day loading rate, it appears that pure cow manure has the best profitability with an NPV of $18.2 million over the course of the 16-year digester lifetime. As cow manure is swapped out for pig manure, the NPV decreases, dropping to a low of $8 million at full pig manure. When the pig manure is swapped out for food waste, the NPV continues to decrease whereas at around 52% food waste, there is a dip into a negative, unprofitable NPV. The NPV continues to drop until 100% food waste is obtained before going back up when cow manure begins to swap out the food waste once again.

The UMass Amherst CDM Smith study, stated that their feedstock would consist of 60% wet biosolids (sewage) and 40% source-separated organics (food, yard scraps, paper). Although this is a rough comparison, let’s assume that the 60% wet biosolids is alike cow manure, and the 40% source-separated organics is alike food waste. Where the UMass Amherst CDM Smith case would be in NPV can be seen in Figure 15. It reaches an NPV of $213,000 which is barely profitable in the course of 16 years. In order to make a more accurate comparison, more representative feedstocks such as human waste and compost would have to be inputted into the model.

5. Conclusions and Future Work

As the need to switch to renewable energy sources becomes ever more urgent, it becomes necessary to utilize transitional energy sources to help ease this difficult transition due to current fossil fuel infrastructure. This is where anaerobic digestion technology comes into play which is able to salvage food wastage and uncontrolled landfill methane to produce fossil fuel infrastructure compatible methane. Whether or not building an anaerobic digester is profitable, however, is an important question that anyone would ask before they undertake such a project.

In this study, an existing anaerobic digestion economic feasibility calculator, the URAAD calculator, was modified to incorporate the complexity of the anaerobic digestion process in its biogas and methane production determination. By utilizing a well-known anaerobic digestion math model in combination with a developed simulation, empirical models were able to be developed for biogas production and methane composition when the feedstock composition is varied between binary mixtures of cow manure, pig manure, and food waste [13], [15]. As a result, the capability to vary the feedstock and examine its impact on the project's NPV was able to be added as a new feature. Additionally, a feature was added that automatically calculates the capital cost of the project.

With these new additions to the URAAD calculator, an accessible and process accurate tool has been developed that allows users like farmers, government officials, or anyone else considering building an anaerobic digester, to determine the economic feasibility of the anaerobic digester they would like to build, with varying feedstock composition.

For future direction, the URAAD calculator can still be further improved by developing the automatic calculation of operating costs, annual town taxes, and working capital to take away more of the technical responsibility from the user and make the tool more accessible. Additionally, being able to vary the HRT and TS % in the calculator would be helpful for the user in the case that they want more control to tune and optimize their anaerobic digester.

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