Food waste, manure and digestate derived biochar to enhance biomethane potential in mesophilic anaerobic digestion of food waste

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Abstract

Purpose: Food and animal wastes are attractive substrates for bioenergy production via anaerobic digestion (AD) and pyrolysis because they are produced globally on a large scale. Pyrolysis uses high-temperature treatment in a reduced oxygen environment for the conversion of biomass to bio-crude and biochar, a stable form of nearly pure carbon that has many applications. There is evidence that adding biochar to the AD system can improve process stability and enhance biomethane production. However, there are limited data for biochar addition in digestion of pure food waste substrates.

Methods: Mixed food waste (FW) and dry manure (DM) were converted into biochar using a laboratory furnace. These materials, as well as magnetic biochar produced from digestate, were added to 500 mL digester vessels operated under mesophilic conditions (37ºC) for processing a model food waste substrate.

Results: It was found that biochar provides enhanced stability when added to AD because biochar acts as a buffer in the system. Food waste biochar produced at 500ºC with a 1% loading resulted in an increase of 11.7% in BMP when compared to the control. A techno-economic analysis (TEA) was conducted to understand the value that biochar would offer to an operating digester, assuming a 10% enhancement in methane production with 1% biochar addition.

Conclusions: Food waste tipping fees drive the economics of working AD systems and the addition of biochar offers the possibility of boosting the economics for scenarios where biochar is purchased at low to mid-range prices, or when a pyrolysis system is installed on-site to produce biochar.

Keywords: anaerobic digestion, pyrolysis, biochar, biomethane potential, biorefinery

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1. Introduction

Food waste has been identified as a major sustainability challenge, but excess food materials also have the potential for energy production by thermal or biological conversion techniques (Trabold & Babbitt [1]). Anaerobic digestion (AD) is a widely utilized biological process that converts biomass into biomethane (CH_4) in the absence of oxygen. Recent studies have demonstrated the importance of direct interspecies electron transfer (DIET) in anaerobic digestion, whereby electrons are transferred directly from one cell to another, and thus serves an essential role in stabilizing AD processes by maintaining high methanogenic rate under stressed conditions (Dubé and Guiot [2]). Three fundamental pathways have been identified for facilitating DIET between electron donating bacteria and methanogenic archaea: conductive pili, hair-like structures protruding from the cell surfaces; membrane-bound conductive proteins; and secondary materials in the reaction medium that form a bridge between bacteria and archaea (Park et al. [3]). The third pathway has been explored through studies using granular activated carbon (GAC) that is highly conductive and has a high specific surface area that supports the active microbial community ([4],[5]).

A potentially more sustainable alternative to GAC is biochar, a carbon-rich product of pyrolysis of organic matter under reduced oxygen conditions. The use of pyrolysis to make highly stable carbonaceous materials is a sustainable alternative to landfilling of the solid effluent from industrial or agricultural processes. There are many pathways to the production of biochar, however, slow pyrolysis has mostly been applied because it generally favors greater solid production instead of bio-oil or syngas (Luz et al. [6]). Because biochar is a porous and carbonaceous material, it has proven effective in the immobilization of bacteria and provides support to the anaerobic digestion (AD) process. The addition of biochar to digesters has been shown to shorten digestion starting time, thereby increasing biomethane potential (BMP) while reducing acid stress (Cimon et al. [7]; Mumme et al. [8]).

Activated carbon and biochar are similar materials, the main difference being that biochar is often less expensive to make than activated charcoal, especially if derived from waste feedstocks, but offers many of the same properties. From the extensive literature summarized in reviews published in the past several years ([6], [9]-[15]) , it is known that biochar addition can enhance anaerobic digestion by:

- Accelerating the hydrolysis reaction, and thus shortening the lag time before biomethane production begins.
- Increasing the maximum biomethane yield normalized by the total mass of volatile solids (units of mL/g VS).
- Increasing the reaction rate constant, i.e., achieving the maximum biomethane yield in a shorter time.
- Providing stability when the digester is under "stressed" conditions, such as unusually high or low pH.
- Upgrading biomethane to pipeline quality by adsorbing CO_2, hydrogen sulfide (H_2S) and other contaminants.

There are only a few papers that studied waste management involving mesophilic co-digestion of food waste with dairy manure that has become a common method of converting waste from food processors and retailers such as groceries stores. We are specifically interested in the potential benefits of biochar in anaerobic digestion of food waste in the temperature range of about 35 – 40ºC. Based on our comprehensive assessment of the literature, the current research project was structured to address the following compelling research questions:

- What are the properties of biochar derived from selected waste feedstocks available in the local food supply chain, and pyrolyzed at different temperatures?
- What impacts do these biochar materials have on the mesophilic anaerobic digestion of a model food waste substrate, in terms of maximum biomethane potential?
- Can biochar addition to anaerobic digesters be economically viable at commercial scale, based on the balance between measured benefits in reactor performance and estimated increases in capital and operating costs?

2. Experimental Materials and Methods

There are many feedstocks currently being used to make biochar, including a wide range of waste materials such as food waste. The material from which biochar originates, coupled with the specific pyrolysis process conditions, will largely determine the characteristics of the biochar and its potential uses. This study is specific to understanding the characteristics of biochar from three different waste streams which can aid in the enhancement of anaerobic digestion: food waste, dry manure, and treated digestate (i.e., the effluent from AD systems).

Substrates and sample preparation

Dry manure was obtained from a local dairy farm located in Covington, New York, USA. The samples were stored in a refrigerator until further processing. Food waste from Rochester Institute of Technology's food service was collected and dehydrated for 10 hours and stored until further processing. Prior to producing biochar, the samples were further dried in an oven at 105ºC for 24 hrs.

Biochar production

Biochar was produced using an in-house high temperature furnace (CM Furnaces Inc., Bloomfield, New Jersey, USA). The system allows for the usage of any inert gas for the process and has a microwave system included, although this feature was not used in the current research program**.** The furnace allows for the placement of up to five crucibles and the exhaust system includes a stainless-steel tube placed above the furnace where the condensed bio-oils can be collected and analyzed if so desired. The pyrolysis process was conducted by placing five crucibles containing the raw dry material inside the furnace. The system was heated at a rate of 10ºC/min until the desired final temperature was reached, and there was a 1-hour hold time followed by a cooling phase. Each substrate was processed in a nitrogen environment at two different temperatures (500 and 800ºC). Digestate biochar was identified as MGBC500 and MGBC800 when processed at 500 and 800ºC, respectively. The nomenclature uses "MG" because this material comes from a digester using ferric chloride ($FeCl_3$) to precipitate phosphorous as part of a manure management study. The pyrolyzed digestate was qualitatively determined to be magnetic, consistent with prior research of our group (Rodriguez Alberto et al. [16]). Similarly, DMBC500 and DMBC800 identified dry manure biochar, and FWBC500 and FWBC800 identified mixed food waste biochar, produced at both 500 and 800 ºC.

Surface area and pore size measurements

The NOVAe Series Model 4200 was procured from Quantachrome Instruments. This device has four analysis stations that allow for the determination of surface area, pore size and pore radius. To perform the analysis, approximately 0.2 g of biochar was placed in glass cells and degassed for 24 hours at 105 ºC. The degassed samples were then placed in the analysis stations. The surface area, pore size of desorption and pore radius were measured based on the Brunauer-Emmett-Teller (BET) gas adsorption theory with N_2 as a medium.

Inoculum and substrate preparation

Inoculum was obtained from a commercial anaerobic digester located in Wyoming, New York, USA and degassed at 37ºC for five days to ensure that all available nutrients had all been properly degraded. The substrate used in these experiments was a 10% TS Purina Beneful® dog food semi-solid solution. This material was selected as a model mixed food waste substrate that would offer consistent composition throughout the experimental campaign (25% protein, 8% fat, 9% fiber), a requirement that would have been difficult to maintain using our own mix of food waste. The pellets were mixed with deionized (DI) water in a Vitamix blender until completely homogenized.

Total and volatile solids determination

Clean and dry crucibles were used to weigh the substrate and then placed in a furnace at 120ºC for 20 hours. Afterwards, the samples were removed from the oven and placed in a desiccator until cooled down. The crucible and dried samples were weighed to calculate the total solids contained in the sample, as the ratio of dry and wet weights (W_{dry}/W_{wet} ×100%). To determine volatile solids, the dried samples were then placed in a furnace at 550ºC for 2 hours to create ash (W_{ash}) and weighed again once they reached room temperature (Equation 1):

$$Volatile\ Solids[\%w] = \frac{WDry - WAsh}{WDry} \times 100 \qquad \text{(Eq. 1)}$$

Automatic Methane Potential Test System II (AMPTS II)

Biomethane potential (BMP) was measured using the AMPTS II system procured from Biomass Controls (Lund, Sweden). This instrument provides automated data collection for batch anaerobic digestion systems. Each 500 mL glass bottle represented an independent reactor inoculated in an anaerobic environment and placed in a constant-temperature water bath. The biogas produced in each bottle passed through a 4.0 M sodium hydroxide (NaOH) solution that fixed the CO_2. The resulting gas then reached a detector that provided measurement of the cumulative amount of biomethane (CH_4) produced over a given time.

For reactor start-up, biochar loadings of 0.5, 1, and 2 w/w% were mixed with the dog food substrate and inoculum in 500 mL bottles with a 200 mL headspace. Each reactor had an automated agitator running at 60 rpm that mixed the contents for 10 seconds every 60 seconds. The reactors all had a 2:1 inoculum-to-substrate (I/S) ratio and were prepared based on volatile solids (VS) amounts. The system was first purged with N_2 and then data collection started. Each run took 30 days and data analysis was conducted at the end of each experimental cycle. Equation 2 provides the calculation to determine BMP:

$$BMP\ \left[\frac{mL}{gVs}\right] = \frac{V_s - V_b \times \left(\frac{m_{Is}}{m_{Ib}}\right)}{m_{S_s,V_s}} \qquad \text{(Eq. 2)}$$

where;

BMP	=	biomethane potential, the normalized volume of methane produced per gram of volatile solids (NmL/gVS)
V_s	=	cumulative volume of methane produced from the reactor with the sample (NmL)
V_b	=	mean value of cumulative volume of methane produced by the three blanks (NmL)
m_{IS}	=	total amount of inoculum in the sample (gVS)
m_{Ib}	=	total amount of inoculum in the blank (gVS)
$m_{Ss,VS}$	=	amount of organic material of substrate contained in the sample bottle (gVS).

An example of the raw output from the AMPTSII system is provided in Figure 1, for one of the samples run with pure dog food (i.e., without added biochar). As can be seen, for this substrate material rich in proteins and carbohydrates, methane production begins very rapidly with a short lag time. Most of the methane production occurred in the first 10 days, whereas only an additional 54 mL was generated between days 11 and 30. To compute the final BMP value according to Equation 3, the cumulative amount of methane generated after 30 days (in this case, 828 mL) was normalized by first subtracting the mean amount of methane produced by the blanks (i.e., inoculum only). Then, this value was corrected for the difference in inoculum mass between the sample and the blank, and then divided by the mass of organic material (in grams volatile solids) present in the sample bottle.

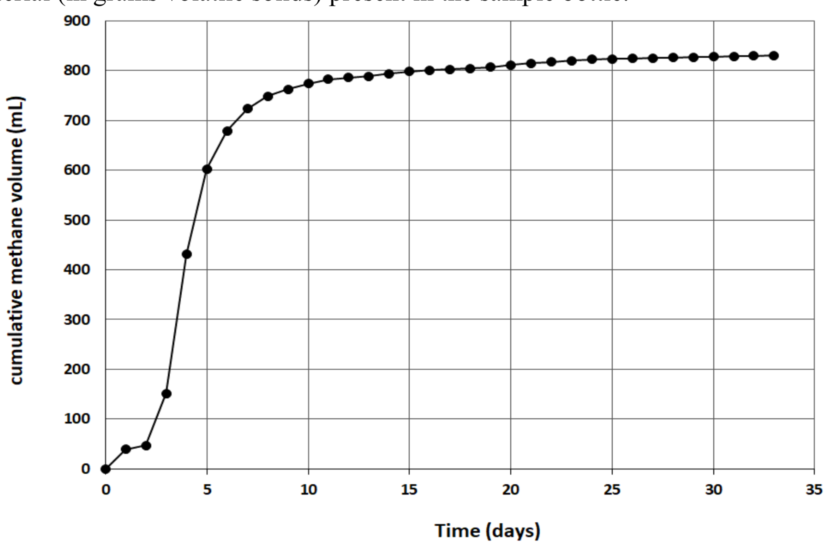

Figure 1 – Example of raw cumulative methane volume data generated by AMPTS II system during mesophilic digestion of food waste

3. Experimental Results and Discussion

3.1 Biochar characterization results

This results of the characterization experiments for the six biochar materials produced from dry manure, food waste and digestate (DMBC500, DMBC800, FWBC500, FWBC800, MGBC500, MGBC800) include measurements of yield, pH, surface area, mean pore volume, mean pore surface area, and mean pore radius (Table 1).

<u>*Biochar yield*</u>

Factors such as temperature, biomass source, and holding time influence biochar yield, as does material density. All biochar samples followed the expected trend, with higher temperatures resulting in lower yield (Table 1). Biochar processed at higher temperatures have shown to have a lower yield than those processed at 800ºC, and this can be attributed to the complete carbonization of the feedstock material. Magnetic biochar derived from digestate was found to have the highest yield among all the biochars produced, 48.73 % for MGBC800 and 62.00 % for MGBC800. This result is attributed to the higher density created when treating the digestate with ferric chloride to extract the phosphate in the original digestate material. The yields for DMBC and FWBC were within the normal range expected for biochar, 31.48% for DMBC500, 29.05% for DMBC800, 33.53% for FWBC500, and 28.20% for FWBC800.

pH

The pyrolysis of biomass has been shown to affect pH, resulting in increases in alkalinity and changes in ash content. Higher pyrolysis temperature results in an increase of surface area, carbonized fractions, pH and volatile matter and a decrease of cation exchange capacity (CEC) and content of surface functional groups (Tomczyk et al. [17]). A study by Cantrell et al. [18] showed that biochar from dry manure had a higher pH with increased pyrolysis temperature, also confirmed in the present study (Table 1). Biochar produced from food waste at 500 ºC had the lowest pH; this can be attributed to the feedstock source itself, since food waste is rich in cellulose and other sugars. In the case of dry manure feedstock, the resulting biochar had pH of 9.66 when processed at 500 ºC and 11.64 at 800 ºC. This is due to the separation of salts, calcite and quartz which is attached to the hemicellulose of the manure (Cao and Harris [19]). Among all biochar samples, the highest pH was found in the digestate biochar, MGBC. Since this biomass was pretreated with ferric chloride, it has a higher level of alkali salts which increased in concentration as the carbonization of the material increased. The pyrolysis process increases the ash concentration in biochar, which would also explain the relatively high pH.

Surface area and pore size analysis

Pyrolysis temperature has an effect on the physicochemical characteristics of biochar, impacting pore size and surface area in the same way as it does pH. Processing temperature and biomass sources can affect the potential biochar applications ([17],[20]). After pyrolysis, there are more cracks of the compounds present in the surface of the biochar which increases pore depth, and this is due to pore blocking substances being driven off by increasing temperature. These compounds are thermally cracked and pores are formed, increasing in turn the surface area while lowering particle size ([17],[21]). The presence of amorphous carbon structure increases with temperature and cellulose containing biochar might be better at capturing aromatic compounds and acting as better adsorbents [17].

Table 1 - Characterization of biochar samples derived from various feedstocks processed at 500 and 800 ºC [DMBC = dry manure biochar; FWBC = food waste biochar; MGBC = magnetic digestate biochar]

Name	Yield (%)	pH	Surface area (m^2/g)	Mean pore volume (cm^3/g)	Mean surface area of desorption (m^2/g)	Mean pore radius (nm)
DMBC500	31.48	9.66	3.28	0.0040	2.77	2.02
DMBC800	29.05	11.54	8.98	0.0043	2.58	2.02
FWBC500	33.53	8.94	2.43	0.0033	2.05	2.46
FWBC800	28.20	10.24	6.38	0.0040	2.79	2.01
MGBC500	62.00	10.65	6.31	0.0085	5.80	2.04
MGBC800	48.73	12.10	98.83	0.0270	19.62	2.04

MGBC has the highest surface area and pore volume, which can be attributed to smaller metal particles that are attached to the surface of the biochar during the pretreatment of the digestate. There is a direct relationship between the increase in pyrolysis temperature and the increase of surface area. The lowest surface area was found on FWBC500 with 2.43 m^2/g, followed by 3.28 m^2/g for DMBC500, 6.31 m^2/g for MGBC500, 6.38 m^2/g for FWBC800, 8.98 m^2/g for DMBC800, and 98.83 m^2/g for MGBC800. The results show an increase in surface area and pore size with temperature, however with the exception of MGBC800, all the biochar have a relatively low surface area compared to many of the prior literature studies. Because the BET analysis was performed with N_2 gas instead of a smaller gas molecule such as CO_2, there is the understanding that the surface area analysis was not comprehensive because N_2 cannot enter micro- and nano-pores (Weber and Quicker [22]). A more complete analysis that fully interrogates pores of all sizes can be performed using CO_2 or highly wetting liquids like butane.

3.2 Biomethane potential (BMP) impact of biochar addition

<u>*Food waste biochar*</u>

Figure 2 shows the biomethane potential (BMP) results for the two food waste biochar samples, FWBC500 and FWBC800. The highest BMP obtained during this run was from the addition of FWBC500 with a 1% loading of biochar (Note: all loading values are mass percentages). This resulted in 410 mL CH_4/gVS, which amounts to an increase of 11.8% when compared to 367 mL CH_4/gVS from the control group (i.e., dog food only). FWBC500 showed an optimal BMP at 1%, while the lowest was at 2% loading with 368 mL CH_4/gVS. In the case of FWBC800, the highest BMP was found to be with a 2% loading which amounted to a 7.2% difference compared to the control. The characterization data presented in Section 2 showed that lower pH was found at lower processing temperatures. In this case, FWBC500 had the lowest pH among all the biochar samples. Since the biochar substrate is similar in composition to the substrate during AD, there is a more direct relationship which allows for a better buffering capacity in the reactor. In this case the temperature of processing of the biochar did not have the expected results. The higher surface area and pore size was achieved at 800 ºC, however, the highest BMP was found from a biochar with the lower processing temperatures.

<u>*Dry manure biochar (DMBC)*</u>

Dry manure was the most consistent feedstock obtained for conversion to biochar. The material was dried prior to processing which allowed for the extraction of moisture enclosed within the surface of the substrate and can explain the increase in surface area of this biochar once converted. The maximum BMP obtained for these experiments was with DMBC500 with a loading of 0.5%. The BMP for that specific biochar loading was 427.6 mL CH_4/gVS, and accounted for a difference of 9.4% in comparison to the control group (391 mL CH_4/gVS). DMBC800 biochar samples followed a trend in which higher biochar loadings decreased the BMP. In the case of DMBC500, however, there was not a clear trend with increased biochar loadings. These results again can be explained by looking at the pH results. Lower alkalinity is found at lower temperature which explains why somewhat higher BMP values were attained with DMBC500. The AD process needs to maintain a near-neutral pH of 7-8. Since biochar acts as a buffer, it needs to provide adsorbent qualities while not disrupting the system by introducing relatively high or low pH that may have a negative effect on the microbial community.

<u>*Magnetic digestate biochar*</u>

Digestate biochar was derived from the effluent of an anaerobic digester treated with ferric chloride ($FeCl_3$) to recover phosphorous for re-use. As shown by Rodriguez Alberto et al. [16] and others, during the pyrolysis process these iron-containing compounds can be converted to magnetite (Fe_3O_4), thus imparting magnetic properties to the biochar. The digestate biochar produced for this research was indeed confirmed to be magnetic. Based on recent literature, this trait was expected to increase the capacity of this specific biochar to increase BMP during AD. However, the result showed similar results as previous runs. The increase in BMP was highest at around 10.83% for MGBC500 with a 2% which amounts to a BMP of 370 mL CH_4/gVS. There is no clear trend for this biochar with an increase in biochar loading. In the case of MGBC800, the BMP results stayed within a close range of each other. The lowest BMP for that biochar was 334 mL CH_4/gVS and the highest was 340 mL CH_4/gVS. At 800ºC, the MGBC showed the highest pH and surface area results. Previous research has determined that higher surface area will have a higher impact on BMP [5], however higher pH in the biochar will tend to offset the buffering capacity that the higher surface area provides [23]. This implies that even when a small increase in BMP is observed, it may still maintain a stable production of biogas.

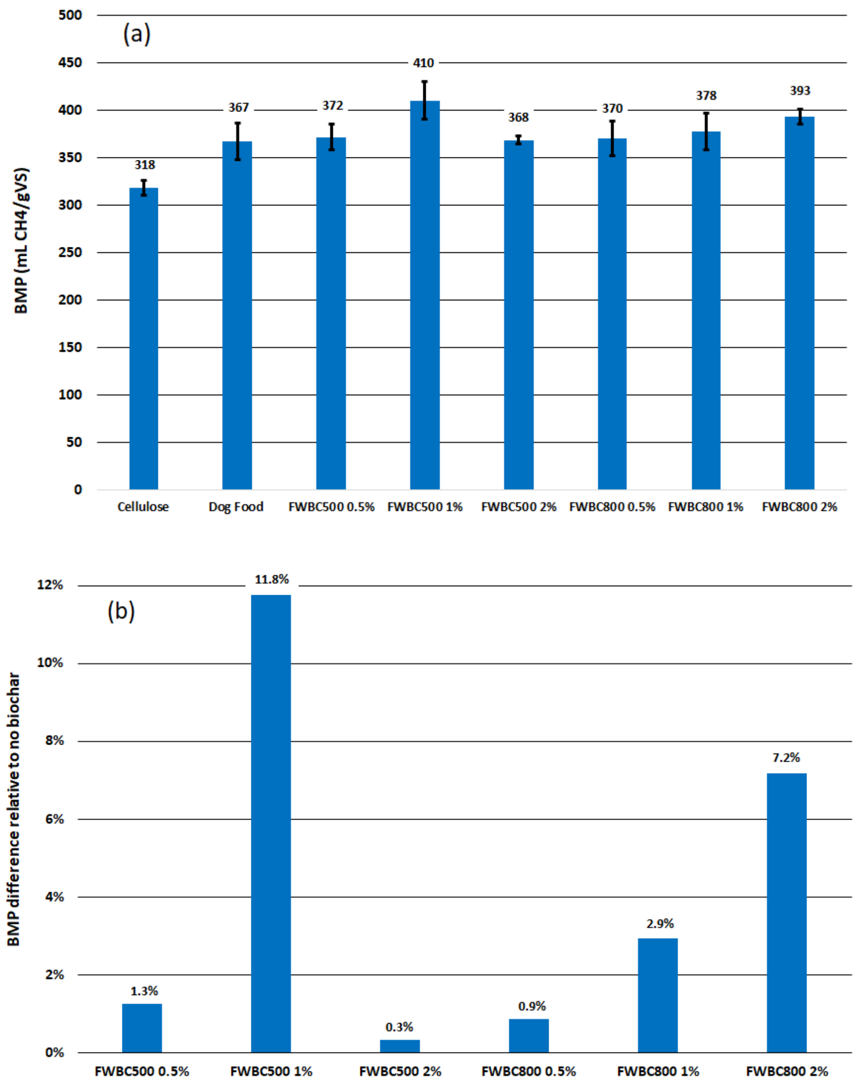

Figure 2 - (a) Biomethane potential and (b) percent difference results (relative to pure dog food) obtained from the runs performed using food waste biochars (FWBC500 and FWBC800). These results were taken from data on Day 30 of the experiment, and error bars indicate one standard deviation of triplicate measurements.

The results of the experiments presented in Section 3 generally showed small enhancements in biomethane potential, regardless of the type of biochar material and mass loading employed. For results presented in Figures 2 and 3, the BMP enhancement relative to the dog food-only baseline ranged from -0.1% for 1% magnetic biochar made at 800 ºC (MGBC800), to +11.8% for food waste biochar made at 500ºC (FWBC500). There is a possibility that the biochar only had a small effect on the AD of dog food because this substrate contains a high fraction of readily degradable material and its ingredients are well balanced. In future research, there is a possibility to explore a substrate which has proven unstable conditions and low BMP. The addition of biochar can play a role in lowering the amount of system shutdowns done when there is an offset in the AD productivity. This would mean lower costs and more diverse substrates can be added to the system which would increase value. In these experiments, biochar samples that were made at lower temperature showed an increase in BMP of around 10% on average. These results indicate that biochar alkalinity in this case plays a bigger part than surface area does. AD is a very sensitive system and the addition of biochar helps it self-stabilize and can potentially increase the economic value.

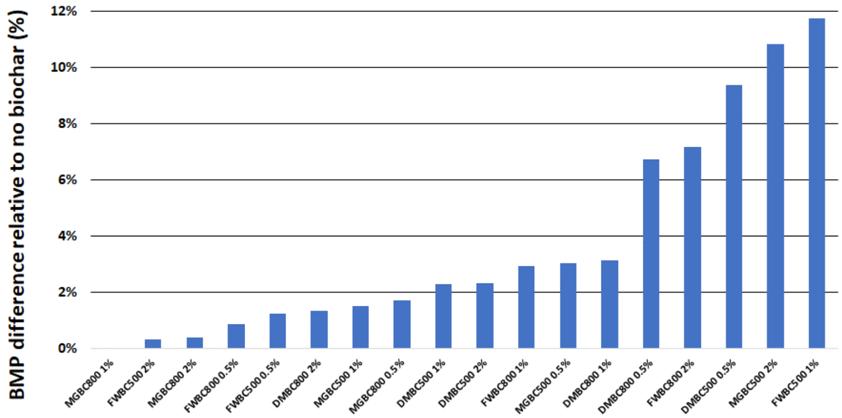

Figure 3 – Percent difference in biomethane potential (BMP) in ascending order for each run and biochar loading

4. Techno-Economic Analysis (TEA)

We explored the economics of biochar addition to a working anaerobic digestion (AD) system by modeling a commercial facility in the Upstate New York region, the subject of previous publications by our research group [24]. This facility is co-located with a large dairy farm managing over 1900 cows that generate manure pumped into the AD system, in addition to food waste from various commercial generators, mostly food processing plants. This AD system has an electrical generator with nameplate capacity of 1.4 MW and accepts around 4.3 million liters of food waste per year. The economic analysis is a matter of assessing the costs of producing or procuring biochar, and the equipment needed to add the biochar to the AD system, versus the value of three potential sources of revenue: additional electrical energy production, additional thermal energy production, and increased tipping fees from accepting more food waste. Although it is expected that renewable energy credits (RECs) and carbon credits may provide additional revenues for AD operation in the near future, to be conservative these credits were not considered in the analysis presented below.

Capital cost (CAPEX) and operation and maintenance costs (O&M)

Capital cost was considered only for purchases associated with adding the capability for biochar addition; the cost of the AD system itself was not included. Because the modeled anaerobic digester would have already been operating without biochar, none of the regular operation and maintenance (O&M) and capital (CAPEX) costs of the baseline AD system were included in the analysis. There have been previous economic studies reporting that the capital cost of a new biochar-producing pyrolysis system is dependent on the amount of waste to be processed, with the average for commercially-available systems estimated at $70 per metric ton of material processed per year (Dickinson et al [25]). For much smaller systems, such as that which would be deployed at the scale of an individual farm, this cost factor is about $200/t. The CAPEX of the pyrolysis system for our model was calculated based on the $200/t factor, multiplied by the amount of biochar needed to provide 1% loading on a yearly basis, assuming a yield of 33% by weight. For the other scenarios in which the biochar is procured from a third party, the prices were estimated as low, mid, and high, and are reported along with relevant capital and O&M costs in Table 2.

The addition of pyrolysis biochar into a working anaerobic digester will also require the installation of an additional piece of equipment that can efficiently add the biochar material upstream of the AD reactor into a batch mixer, currently used to pre-blend the food waste and manure streams. Based on information obtained directly from the AD system operator, and other sources of chemical process equipment costs [27], it was assumed that a capital investment of $50,000 would be needed for equipment to support integrated biochar storage, handling and metering into the batch mixer. This estimate is based on the cost correlation provided for a 0.5 m wide belt conveyor with 5 m length. As described in the analysis presented below, the net present value (NPV) results are not strongly influenced by the assumed cost of the biochar equipment, even if increased by a factor of two. Based on the empirical results presented in Section 3, the economic model assumes that 1% biochar addition produces an additional 10% methane relative to the baseline system without biochar.

Table 2 – NPV model inputs related to biochar and AD equipment and materials, and financial parameters

Parameter	Value	Units	Assumption / Source
Amount of biochar addition	573	t/yr	1% biochar loading, based on total feedstock mass processed at local AD plant in 2019
Biochar price (low)	50	\$/t	25% of the baseline (mid) cost
Biochar price (mid)	200	\$/t	Baseline cost at nominal processing capacity of 100,000 dry t/year [25]
Biochar price (high)	1,000	\$/t	5X of baseline (mid) cost
CAPEX of pyrolysis system	347,000	\$	\$200 per metric ton feedstock processed per year [25]
O&M cost of pyrolysis system	7000	\$/yr	2% of CAPEX (Aui and Wright [26])
CAPEX of biochar metering equipment	50,000	\$	Towler and Sinnott [27]
O&M cost of pyrolysis system	1000	\$/yr	2% of CAPEX [26]
Biogas production rate	3,900,000	m^3/yr	AD plant operation data (2019)
Methane content in biogas	60	%	In-house laboratory data
Annual food waste processed	43,400,000	liter/yr	AD plant operation data (2019)
Annual dairy manure processed	11,200,000	liter/yr	AD plant operation data (2019)
Electricity price	0.06	\$/kWh	www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a
Tipping fee	52.62	\$/t	EREF [28]
Maturity date	20	yr	Assumed life of AD plant
2020 US discount rate	2.5	%	ycharts.com/indicators/us_discount_rate

Revenue from electrical and thermal energy generation

Consistent with the system architecture of the modeled AD plant, it was assumed that the biogas is converted in an engine-generator set (gen-set) to produce electricity put onto the grid with a value of \$0.03/kWh. The waste heat from the gen-set is recovered through the cooling water jacket, and this thermal energy is used entirely on-site. The value of this thermal energy was computed based on the assumed cost of natural gas that would have otherwise been purchased (\$2.56/MM Btu). These factors allowed for the calculation of electricity generation (EG) and waste heat generation (HG), based on the known methane specific energy (50 MJ/kg) and assumed get-set electrical and thermal efficiencies of 30 and 50%, respectively. After calculation of EG and HG, the income was calculated using the current average wholesale prices for natural gas in the case of HG and electricity in the case of EG.

Revenue from tipping fees

The modeled Upstate New York AD plant was used to determine specific loading of food waste into the digester. The quantity of waste was calculated for each scenario taking into account an increased loading of food waste of 1, 5, 10 and 20 weight% greater than the baseline system, assumed to be enabled by the stabilizing effect of adding 1% by weight of biochar to the total amount of food waste and manure being processed. The tipping cost was obtained from the 2019 average U.S. landfill tipping costs, as reported in Table 2. It is assumed that food waste generators would be motivated to direct waste to the AD plant instead of the landfill if there is not an economic penalty to do so.

Net present value (NPV) model

The net present value (NPV) was used to determine the financial viability of 4 scenarios: procuring a pyrolysis system to produce biochar on-site (Scenario 1), and procuring biochar based on low, mid and high prices of \$50, \$200 and \$1000/t, respectively (Scenarios 2-4). The lifetime was only considered for the procured biochar addition equipment and pyrolysis system, and it was assumed that the AD system would be working for 20 years from the first time biochar was added to the system. The NPV was calculated taking into consideration that the addition of more food waste into the system would increase the biochar addition requirement, tipping fees, and the enhanced methane generation would remain as 10% of the methane that would have been generated from the total food waste + manure without biochar. NPV was calculated in 2020 US dollars, and cash flow was determined for each scenario depending on specific characteristics:

$$NPV = -I + \sum_{t=1}^{T} \frac{CF_t}{(1+i)^t} \quad \text{(Eq. 3)}$$

where:

I = initial capital investment (for biochar metering equipment, and also pyrolysis system for Scenario 1)
CF_t = cash flow (revenue – cost) for each year t
i = discount rate = 2.5% (Table 2)
t = year

Figure 4 presents the results of the techno-economic analysis based on the conservative assumption that no government incentives are available, and the financial viability of biochar addition is based entirely on enhanced electrical and thermal energy generation and increased tipping fees. Several interesting trends emerge. First, without incentives, the high biochar cost of $1000/t (Scenario 4) makes the NPV negative regardless of how much additional food waste can be utilized as a result of the stabilizing influence of biochar. The other three scenarios all show conditions under which the addition of biochar may be a sound financial decision. In the case of buying a pyrolysis system for on-site biochar production (Scenario 1), positive NPV is achieved with as little as 1% additional food waste relative to the baseline AD system. However, some cash flow from food waste tipping fees is required to achieve positive NPV, and financial viability cannot be achieved by relying solely on the value of additional electrical and thermal energy production. It is also important to note that procuring pyrolysis equipment (Scenario 1) yields economic outcomes that are essentially equivalent to procuring low cost biochar at $50/t (Scenario 2). This result may motivate an AD system operator to consider purchasing on-site pyrolysis equipment, because maintaining a consistent, high-quality biochar supply at $50/t over the assumed 20 year plant life may be difficult, and to our knowledge is not practical in light of the existing biochar market and supply chain, at least in the U.S.

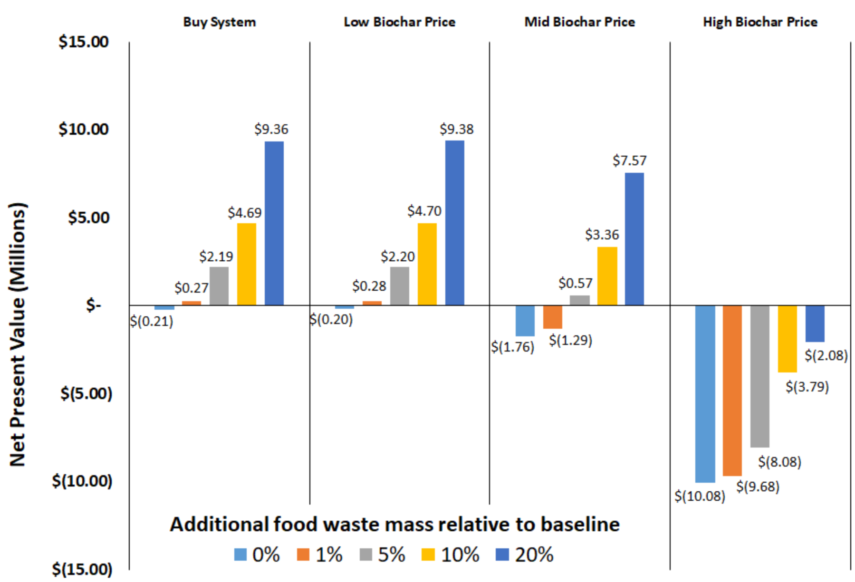

Figure 4 –Net present value (NPV) for the addition of biochar to a working AD system, including purchased pyrolysis system for biochar production and low/mid/high costs of purchased biochar. The impact of increasing food waste processing of 1, 5, 10 and 20% of the baseline are indicated. Incentives such as renewable energy and carbon credits are not included in the annual cash flow.

5. Conclusions and Future Work

Biochar can benefit anaerobic digestion (AD) processes in a number of ways, including increasing the level of biomethane production, and increasing system stability to enable processing of a greater fraction of food waste in co-digestion with animal manure. The addition of biochar to the AD of food waste was studied to understand the relationship between the addition of adsorbents in the process and the increase in BMP. Adsorbents help reduce the presence of inhibitors, and this is attributed to the pH more so than the surface area. It was found that lower processing temperature during pyrolysis resulted in lower pH, surface area, and pore size. The experimental results showed that better BMP results were achieved between 0.5 and 1% loading. However, there is still a need to understand the specific types of biochar that would work best for each available condition and substrate. More AD experiments can help shed light to the degree in which the results would be different with the used of stressed conditions such as increased levels of inhibitors, or unusually high or low pH. Because the experiments were done in a batch system, it lacks the ability to be continuously fed as would be done for an industrial scale.

There are still gaps to be filled due to the lack of information regarding the surface properties of the biochar samples, and how they can influence fundamental biochemical processes, such as direct interspecies electron transfer (DIET). Additional characterization including scanning electron microscopy (SEM) and elemental analysis should be performed to determine the exact composition and morphology of each biochar sample. Future work should compare thermophilic and mesophilic AD systems to assess the upgrade of biomethane production, and further understanding of how the addition of biochar can help recover a deteriorated AD system or a system working with substrates with low yields of biomethane. Various combinations of substrates can also be used to determine if the results are similar to those obtained in the current study. Other experimentation should also focus on the use of biochar derived from substrates widely available in our region such as crop residue, cardboard waste, and untreated digestate.

The techno-economic analysis (TEA) model quantified the added value from the enhanced stability by the addition of biochar to an industrial scale AD system. Since there is no way for the AD operator to control the biochar market price and supply chain stability, the best choice may be to install an on-site pyrolysis system which will allow for an increase of up to 20% of the baseline food waste loading. This economic analysis, however, was based on many assumptions that fit the profile of a local AD system. Further work would focus on the inclusion of the pyrolysis system energy usage and substrate costs since the present study assumes that the substrate would be available at no cost.

Acknowledgements

We acknowledge the Golisano Institute for Sustainability at Rochester Institute of Technology (RIT) for providing a partial tuition scholarship for C.B. Frias Flores. This paper is based on the thesis submitted for the M.S. Sustainable Systems degree at RIT [29]. The authors also acknowledge Waste Management, Inc. for providing support for C.B. Frias Flores to attend the 8th International Conference on Sustainable Solid Waste Management.

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