sustainability

MDPI

Article

Anaerobic Co-Digestion to Enhance Waste Management Sustainability at Yosemite National Park

Julia Burmistrova [1], Marc Beutel [1,*], Erin Hestir [1], Rebecca Ryals [1] and Pramod Pandey [2]

[1] Environmental Systems Graduate Group, University of California, Merced, CA 95343, USA
[2] Biological and Agricultural Engineering Department, University of California, Davis, CA 95616, USA
* Correspondence: mbeutel@ucmerced.edu

Abstract: This study evaluated the co-digestion of domestic wastewater solids (WWS) and food waste (FW) at the bench-scale for Yosemite National Park, California, which operates a 1900 m^3/d wastewater treatment plant in El Portal, California. A 35-day biochemical methane potential test was performed on varying amounts of FW as a percentage of total waste (WWS plus FW) on a volatile solids basis (%FW). Specific methane yield and volumetric methane yield increased substantially with increasing %FW. A higher %FW was also associated with slower degradation kinetics but higher methane content in biogas. The 75 %FW treatment had relatively rapid kinetics, a high cumulative specific methane yield (453 mL CH_4/g VS), and an elevated methane content in biogas, and is suggested as an upper limit %FW mixture for full-scale co-digestion. This, coincidently, is near the estimated ratio of WWS and FW production at the Park (70 %FW). Co-digesting the Park's feedstock of FW with WWS in existing anaerobic digestion facilities could increase methane production five-fold. Combusting this methane in a combined heat and power system would produce about twice the energy needed to heat anaerobic digestors and power the treatment plant.

Keywords: biochemical methane potential test; combined heat and power; food waste; wastewater solids

Citation: Burmistrova, J.; Beutel, M.; Hestir, E.; Ryals, R.; Pandey, P. Anaerobic Co-Digestion to Enhance Waste Management Sustainability at Yosemite National Park. *Sustainability* **2022**, *14*, 11877. https://doi.org/10.3390/su141911877

Academic Editor: Luis Jesús Belmonte-Ureña

Received: 18 June 2022
Accepted: 18 September 2022
Published: 21 September 2022

1. Introduction

"Thou shall not waste potential energy" is the first commandment for developing a sustainable society [1]. An important and unused potential energy source in many communities is organic municipal solid waste, which is commonly dominated by food waste (FW). Globally, organic waste accounts for a significant portion of municipal solid waste (30–65%), and the production of municipal solid waste is growing, having nearly doubled over the past decade to an estimated 2 billion tons per year [2]. The anaerobic co-digestion of wastewater solids (WWS) with organic solid waste is a compelling approach to capture the potential energy of organic solid waste while enhancing the sustainability of wastewater and solid waste management [3–8]. WWS typically include settleable solids in inflowing wastewater and microbial biomass produced during the biodegradation of organic matter. WWS are commonly treated using anaerobic digestion, which produces methane-rich biogas that can be harvested as an energy source [9]. Wastewater treatment plants are ideal locations for co-digestion since many plants have surplus digester capacity [10–12]. Additionally, much of the wastewater infrastructure in the US is outdated [13], offering a unique opportunity to integrate organic solid waste treatment with upgraded anaerobic co-digestion facilities.

The co-digestion of FW with WWS provides some advantages compared to digesting these substrates separately or landfilling organic municipal waste. FW alone is a challenge to digest anaerobically because its breakdown produces elevated concentrations of volatile fatty acids (VFAs) that lower pH and inhibit methanogenesis [8,11]. By mixing FW with a co-substrate such as WWS, the combined substrates are easier to digest, produce more biogas relative to digesting FW alone, and tend to promote a more robust microbial community [3,4,8,14]. Another benefit is that methane produced from FW in an anaerobic digester is easier to harvest and is generally of better quality (e.g., higher energy content, lower sulfide) than that produced by FW disposed in a landfill [15,16]. Energy production from WWS biogas alone can typically supply ~50% of a wastewater treatment plant's energy needs, compared to 100% or more when co-digested with FW [5,7]. For example, East Bay Municipal Utility District in Oakland, California, USA co-digests 120,000 kg/d of organic municipal waste and produces enough energy to power its entire wastewater treatment process, which serves around 685,000 people [10]. The implementation of 20 %FW co-digestion in existing anaerobic digesters at a wastewater treatment plant in Grüneck, Germany serving around 73,000 people yielded a 16% increase in energy self-sufficiency and had a pay-back period of 10 months [12]. The wastewater treatment plant in Manteca, California, USA serving around 81,000 people is co-digesting commercially generated FW in expanded anaerobic digester facilities and producing 500 diesel gallon equivalents per day of automobile fuel as renewable compressed natural gas [17].

This study examined the feasibility of the anaerobic co-digestion of WWS and FW to enhance waste management in Yosemite National Park (Park), CA, USA. The Park, a leader in sustainability and resource management, intends to fully divert solid waste away from landfills over the coming decade [18]. The Park is also redeveloping its wastewater treatment plant in El Portal, California. This provides a unique opportunity to use anaerobic co-digestion to enhance waste management at the Park. The study is unique in that, in addition to conducting a site-specific assessment of co-digestion methane production potential, a waste inventory at the Park was used to estimate the potential for biogas produced via co-digestion to meet the energy needs of the Park's wastewater treatment plant.

The study's aims were three-fold. First, the mass and quality of FW and WWS produced in the Park were assessed to inform future co-digestion scenarios. Second, a biochemical methane potential (BMP) assay was used to assess methane production as a function of the percentage of total waste as FW on a volatile solid basis (%FW). Performing this assay on the specific waste at hand is important because the co-digestion process depends on the unique quality of local waste feeds [19]. In addition, it can be a challenge to use the literature BMP values to predict biogas production, since methods vary considerably [20–22]. Third, BMP results were used to assess the potential for full-scale co-digestion at the Park's wastewater treatment plant to meet the energy needs of the plant using a combined heat and power system. The preliminary results indicate that the co-digestion of FW at the Park's existing anaerobic digesters could result in a substantial increase in methane production, and the energy harvested from the gas would exceed the energy demand to heat the digester and power the plant.

2. Materials and Methods

2.1. Study Site

Yosemite National Park is located in the western Sierra Nevada mountains of central California, USA (37.8651° N, 119.5383° W) and is one of the most popular outdoor travel destinations in the world. However, its expansive wilderness (3000 km^2), complex topography (ranging from 600–4000 m), and large visiting population (4–5 million visitors per year) make waste management a challenge. The Park landfills an estimated 2 million kg/year of municipal solid waste and diverts another 4.2 million kg/year of recyclable solid waste material [23]. Of this waste, an estimated 1 million kg/year of FW is available for co-digestion. Most wastewater produced at the Park undergoes treatment at a wastewater treatment plant in El Portal, California near the western entrance of the Park. The treatment plant was originally constructed in the 1970s. Its treatment capacity is 3800 m^3/d, and its annual average inflow is 1900 m^3/d. The treatment plant anaerobically digests an estimated 5.1 million kg of primary wastewater solids per year (Table S2) in two single-stage mesophilic digesters; produced biogas is currently flared to the atmosphere. After anaerobic digestion, an estimated 375,000 kg/year of dried biosolids are transported for land application on non-consumable crops. The treatment plant is slated for a multimillion-dollar upgrade, presenting waste managers with an opportunity to design a new system to treat both FW and WWS via co-digestion. This new system could potentially produce enough biogas to power the wastewater treatment plant while diverting solid waste from landfills.

2.2. Collection and Characterization of Waste

Inoculum and WWS were collected from the El Portal wastewater treatment plant's anaerobic digester and primary clarifier, respectively. Both were stored in covered 7 L plastic buckets for transport. FW from the Park was collected in a covered 22 L plastic bin on the same day that the Park waste was delivered to the Mariposa County landfill. In the laboratory, FW was blended in a food processor, and the slurry was stored in covered 7 L plastic buckets. Inorganic contaminants found in the FW, including paper cups, glass, plastic items, and metal bottle caps, were discarded prior to blending. All substrates were refrigerated until further use. Prior to BMP measurements, substrates were analyzed for total solids (TS) and volatile solids (VS) using standard methods [24]. The displacement method was used to measure FW density, and mass and volume measurements were used to calculate WWS density. In this study, the annual production of WWS at the Park was calculated based on 2017 data from the El Portal wastewater treatment plant (Harders, G., personal correspondence); annual FW production was based on a recent characterization study of solid waste produced at the Park [23].

2.3. Biochemical Methane Potential

BMP incubations were performed on FW and WWS mixtures based on the approaches outlined in [19,25]. Triplicate treatments were performed for 0, 10, 25, 50, 75, 90 and 100 %FW and an inoculum control. For all treatments, the total volume was maintained at 150 mL and the inoculum to substrate ratio was maintained at ~1:1 on a VS basis to maintain relatively similar conditions in all treatments. Volumes of inoculum, WWS and FW were adjusted accordingly (Table S1). Target amounts of FW, WWS, and inoculum were added to 200 mL bottles, sealed, and placed on an orbital shaker set to 150 revolutions per minute in a dark incubator stored at mesophilic conditions (35 °C). Over a 35-day duration, every 1–5 days, biogas was sampled from incubations, depending on the production rate of biogas. Gas samples were first collected for gas composition analysis with a 30 mL plastic gas sampling syringe and stored in 15 mL exetainers (Labco Limited, Lampeter, Wales, UK). The remainder of the gas volume was measured using a wet-tipped glass 50 mL syringe until the bottles equilibrated to atmospheric pressure. Gas composition was measured using gas chromatography (GC) (Trace 1300, S/N 119900-0115, Thermo Fisher Scientific). The GC temperature was set to 250 °C for injection and 300 °C for the detector. The carrier gasses used were compressed air (400 mL/min) and hydrogen (150 mL/min). To use the GC autosampler, a subsample of biogas from the exetainers was diluted 40 times by volume in crimped 20 mL glass vials. The pH of the incubation contents was measured at the start and the end of the BMP using a calibrated pH meter.

2.4. Analysis of Data

Cumulative methane production was normalized in two ways. Specific methane yield (mL CH_4/g VS substrate added), a commonly accepted anaerobic digestion metric, was estimated by normalizing to VS of feed. Volumetric methane yield (mL CH_4/mL substrate added), a metric useful for wastewater managers who use volumetric loading to operate digesters [25], was also estimated by normalizing to volume of feed. Both metrics were corrected for methane produced by inoculum, which was minimal. The results of BMP incubations are reported as the averages of triplicate incubations. R software's base stats package (version 3.5.2) was used to assess specific methane yield, volumetric methane yield, and biogas methane content as a function of %FW via linear regression. The standard error of key biogas metrics associated with triplicate BMP incubations was also estimated.

The relative standard error measured during the multiple sampling events of the 35-day incubation typically ranged between 3 and 13% for specific methane yield and volumetric methane yield and between 1 and 4% for methane content. Errors are reported in Table S3 and shown in Figure S1.

3. Results

3.1. Waste Characterization and Waste Production at Park

WWS, FW, and inoculum had similar densities (~1 g/mL), indicating that the substrates had a high fraction of water (Table S2). On a mass basis, FW had approximately ten times more VS than WWS (0.31 g/g versus 0.029 g/g), highlighting the relatively high VS content of FW. FW had a density (1.10 g/mL) higher than the typical values in the literature (0.4–0.8 g/mL) [26], but the percent VS in FW was typical of values from other studies (92%) [27]. In terms of total mass, the Park produces an estimated 5.1 million kg/year of WWS and 1.0 million kg/year of FW (Table S2). This is equivalent to 150,000 kg VS/year of WWS and 320,000 kg VS/year of FW. Consequently, although there is more volume and mass of WWS, there is actually more kg VS of FW.

The %FW (VS basis) of annual waste production from the Park is around 70%. While the amount of waste produced at the Park is highly seasonal and peaks in the summer, the amount-of-FW-to-WWS ratio by VS is anticipated to remain relatively constant since both solid waste and wastewater are dependent on the number of visitors in the Park. Seasonal trends in visitor attendance correspond with trends in WWS production, confirming the link between visitation and waste production (Figure 1). These data also indicate an annual monthly waste production peaking factor (peak month/annual average) of around two. FW VS content tends to be constant on a weekly to monthly basis [27,28]. Thus, the resulting %FW of 70% calculated here is a reasonable metric on the basis of which to make a preliminary assessment of the potential for co-digestion at the Park's El Portal wastewater treatment plant. Total visitation to the park has remained relatively steady over the past 10 years, typically ranging from around 4–5 million per year, excluding the low visitation during COVID years.

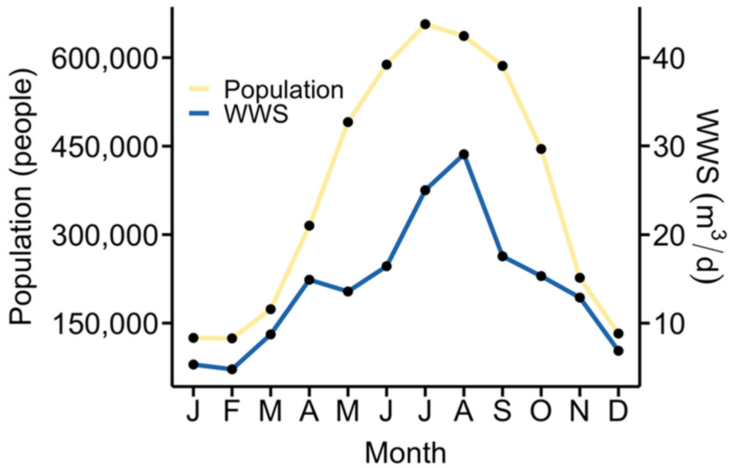

Figure 1. 2017 Yosemite National Park visitor population and El Portal wastewater solids (WWS) production. Visitation statistics from: https://www.nps.gov/yose/planyourvisit/visitation.htm (accessed on 28 April 2020).

3.2. Biochemical Methane Potential

The patterns of methane production in BMP incubations showed clear trends related to incubation duration and %FW (Figure 2, Table S3). The specific methane yield showed the classic "S" curve, with peak methane production (curve inflection point) occurring around day 8 for 0–25 %FW and day 14 for 75–100 %FW. Longer times to peak production were also associated with the later plateauing of specific methane yield values, which was especially apparent in the 90 and 100 %FW treatments. The values of cumulative specific methane yield at 35 days ranged from 267 mL CH_4/g VS at 0 %FW to 478 mL CH_4/g VS at 100 %FW. There was a significant linear relationship between cumulative specific methane yield and %FW ($r^2 = 0.97$, $p < 0.01$; Figure S1). The values of cumulative volumetric methane yield at 35 days ranged from 7.9 mL CH_4/mL at 0 %FW to 135 mL CH_4/mL at 100 %FW, highlighting the potent methane production potential of FW on a volume basis. There was also a significant log-linear relationship between the cumulative volumetric methane yield and %FW ($r^2 = 0.95$, $p < 0.01$; Figure S1). The methane content of biogas in all treatments was 60–70% after 10 days, with the 90 and 100 %FW treatments showing a slight temporal lag compared to other treatments. A significant linear relationship between methane content averaged over the last 15 days of the incubation and %FW was also observed ($r^2 = 0.93$, $p < 0.01$).

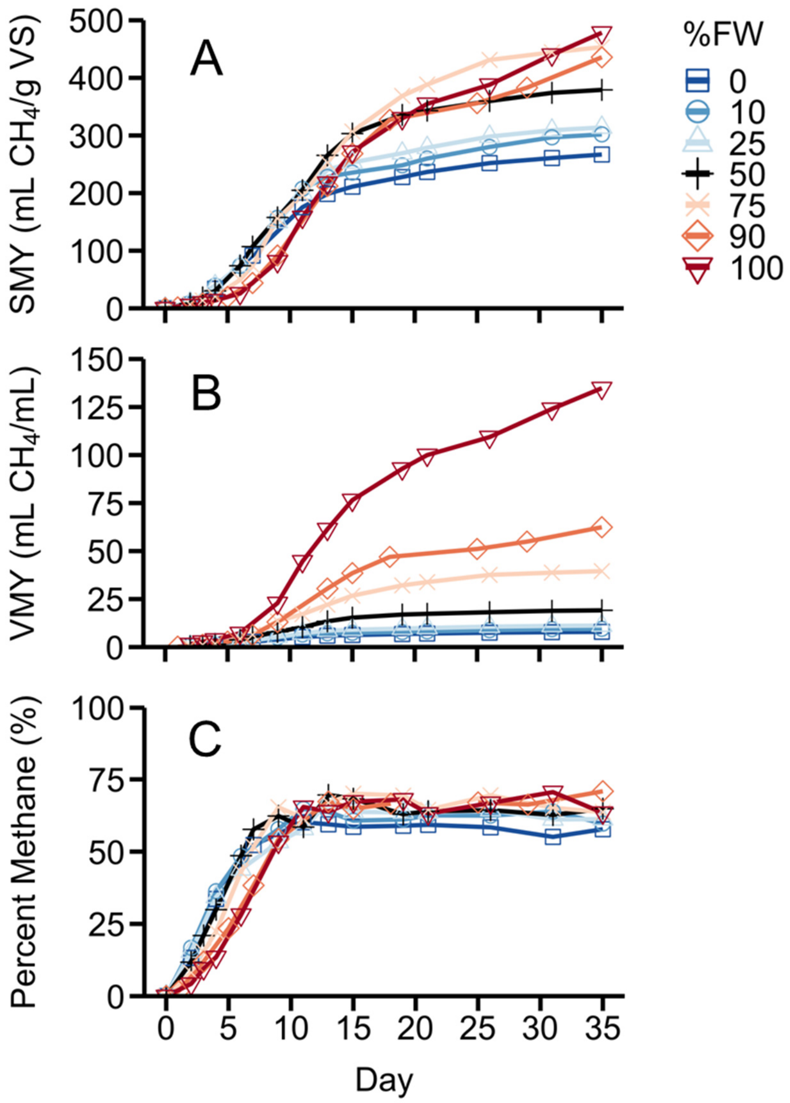

Figure 2. Methane production as a function of percent food waste (%FW) in BMP incubations. (**A**) Cumulative specific methane yield (SMY). (**B**) Cumulative volumetric methane yield (VMY). (**C**) Biogas methane content. Data points are mean values of triplicate incubations. Relative standard error of triplicate measurements typically ranged between 3 and 13% for specific methane yield and volumetric methane yield and between 1 and 4% for methane content. See data in Table S3 and Figure S1, which include standard error estimates.

4. Discussion

4.1. Biochemical Methane Potential

The substitution of WWS with FW (i.e., increasing %FW) led to a significant increase in methane production on a VS mass basis and a waste volume basis. The results highlight the relatively high concentration and digestible nature of the VS found in FW relative to WWS. In the context of this study, an increase from 0 to 75 %FW, the approximate %FW ratio of waste produced at the Park, enhanced specific methane yield by a factor of 1.7, from 267 to 453 mL CH_4/g VS, and volumetric methane yield by a factor of 5, from 7.9 to 39.5 mL CH_4/mL.

Comparing across BMP studies is challenging due to a lack of standardized methods [21,22], but this study's values were typical of BMP results for the co-digestion of organic substrates [4,8,10,20,21,29] (Table 1). Ref. [25] reported BMP specific methane yields of 125–452 mL CH_4/g VS for a range of FW-manure treatments. Ref. [30] assessed biogas production in bioreactors fed with dewatered WWS (0.11 g/g VS) and FW (0.19 g/g VS). They observed a linear increase in specific methane yield with increasing %FW, which ranged from 237 mL CH_4/g VS for 0 %FW to 465 mL CH_4/g VS for 100 %FW over a 30 d duration. [31] also observed a linear increase in specific methane yield ranging from 285 mL CH_4/g VS to 520 mL CH_4/g VS using synthetic FW mixed with sewage sludge, with assays ranging from 0 to 100 %FW. While the numerical values of specific methane yield vary across studies, there is a general trend of around a doubling of specific methane yield when co-digesting wastewater feed stocks with a high fraction of FW. Clearly, the co-digestion of WWS with FW can substantially enhance methane production and the related potential for energy generation.

Table 1. Specific methane yield from comparable co-digestion studies.

Co-Digestion Feed Stock	Select Treatments (% VS)	Specific Methane Yield (mL CH_4/g VS)	Citation
Wastewater Solids and Food Waste	0% food waste 50% food waste 100% food waste	267 379 478	This Study
Manure and Food Waste	100% manure 19% manure, 81% cranberry 16% manure, 84% chicken	92 200 381	[25]
Wastewater Solids and Food Waste	0% food waste 50% food waste 80% food waste	116 215 257	[29]
Wastewater Solids and Food Waste	0% food waste 53% food waste 100% food waste	237 350 465	[30]
Wastewater Solids and Food Waste	0% food waste 50% food waste 100% food waste	285 410 520	[31]

Note: Reported results are for ~30–35-day BMP incubations under mesophilic conditions (~35 °C).

A pattern of note in our study was the slower degradation kinetics in the 90 and 100 %FW treatments. The peak rate of methane production was around a week later for these treatments compared to the lower %FW treatments (Figure 2A). In addition, the treatments had lower methane contents in biogas in the early days of the BMP incubation (Figure 2C). For example, the methane content at day five was around 35% for 0–50 %FW treatments, but it was only 20% for 90–100 %FW treatments. The slower kinetics and lower methane content associated with higher %FW treatments may have been related to the inhibitory effects of elevated VFA concentrations associated with high FW concentrations [11,32]. In this study, there was a moderate pH increase (0.2–0.3 pH units) with increasing %FW (Table S3). Slower kinetics at higher %FW also could be related to the larger size and semi-solid nature of the FW in this study. Hydrolysis during anaerobic digestion is acknowledged as a rate-limiting step [4,8,33], and the large particle size of FW has been associated with lower rates of hydrolysis in some studies [34].

The 75 %FW treatment had relatively rapid kinetics, a high cumulative specific methane yield, and an elevated methane content in biogas, and it is suggested as an upper limit %FW mixture for full-scale co-digestion. This, coincidently, is near the estimated ratio of WWS and FW production at the Park (70 %FW). Another observation of interest was the slightly higher methane content in biogas for the higher %FW treatments (Figure 2C). This contrasts with the results from [30,35], which tended to show an opposite trend. However, [25] reported a higher methane content in biogas with increasing %FW in FW-manure treatments.

4.2. Co-Digestion Energy Balance at the El Portal Wastewater Treatment Plant

Keeping in mind that small-scale lab BMP assays tend to overestimate methane production [20,36], the BMP results were used to perform a preliminary evaluation of FW co-digestion and biogas energy production at the El Portal wastewater treatment plant (Figure 3). According to billing statements from 2018 to 2019, the plant uses ~500,000 kwh/year for digester heating and an additional ~200,000 kWh/year for various plant operations.

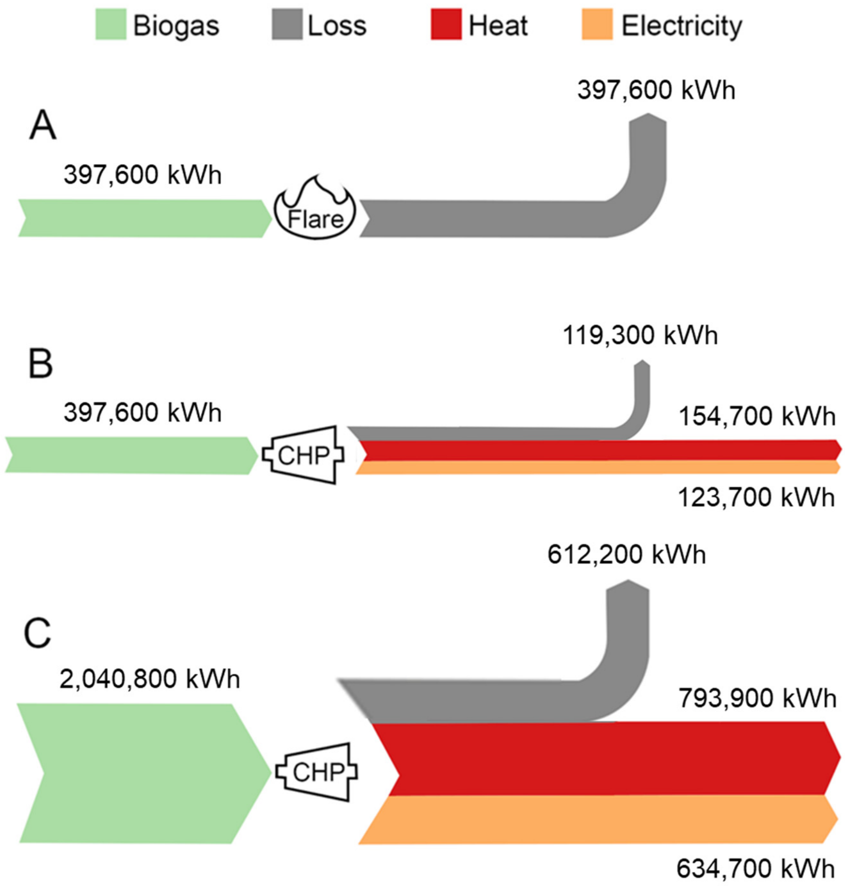

Figure 3. Schematic of annual energy balance for three scenarios: (**A**) current conditions; (**B**) current conditions with biogas energy recovery via combined heat and power (CHP); (**C**) co-digestion of 70 %FW with biogas energy recovery via combined heat and power (CHP). Energy demands at the wastewater treatment plant include 500,000 kWh/year for digester heating and 200,000 kWh/year for other plant operations.

Based on the 0 %FW (WWS only) cumulative specific methane yield results (267 mL CH_4/g VS) and the annual production of VS (150,000 kg), the plant currently flares ~40,100 m^3/year of methane. Putting this methane production in terms of per capita gas production for the El Portal wastewater treatment plant suggests that the BMP results are reasonable. Assuming a per capita wastewater production rate of 200 L/d, the equivalent treatment population for the plant is 9500. Further assuming a 60% methane content yields a per capita gas production of ~19 m^3/d·1000 people, a typical value for the digestion of primary solids [9]. Using a heating value of 35.8 MJ/m^3 [9], the lost energy content of flared methane is ~397,600 kWh/year (Figure 3A).

The Park produces combined organic waste with a %FW of ~70% (320,000 kg VS/year of FW and 150,000 kg VS/year of WWS). The BMP results indicate that 70 %FW has a specific methane yield of 438 mL CH_4/g VS. Thus, co-digestion is estimated to produce ~205,800 m^3/year of methane, with an energy content of ~2,040,800 kWh/year. This is a five-fold increase in biogas production over current operations. Combined heat and power (CHP) is a reliable technology recommended for biogas combustion at small-scale wastewater treatment plants [5,9]. CHP uses gas turbines, steam turbines, or reciprocating engines to co-generate heat and electricity, thereby promoting energy capture efficiency [37]. Assuming a power-to-heat ratio of 0.8 and a 70% overall CHP efficiency [37,38], combusting biogas via CHP would produce considerably more electricity (634,700 kWh/year) than that currently used at the plant and more than enough heat (793,900 kWh/year) to meet the digester heating needs (Figure 3C). The existing anaerobic digestor volume at the El Portal treatment plant is 1260 m^3. For a 70 %FW scenario, the organic loading rate would be ~2 kg VS/m^3·d under summertime peak flow conditions, which is within acceptable limits [9,39]. The seasonal patterns of energy production would need to be considered, since organic waste availability is lowest in the winter when digester heating needs are the greatest.

4.3. Additional Considerations for Co-Digestion

While FW and WWS co-digestion would yield impressive increases in biogas production, increased energy recovery, and cost savings associated with lower rates of landfill disposal of organic solid waste, the process is not without challenges. The pretreatment of FW via biological, mechanical, chemical, or thermal means is commonly recommended to homogenize waste and yield smaller particle sizes that enhance digestibility [4,8]. Additionally, since the current site includes two digesters, managers should consider using a two-stage anaerobic co-digestion process that can improve pH control and methane yield [8,40,41]. Because of greater solids loading, there would be an increase in biosolids production associated with a 70 %FW co-digestion scenario. Co-digestion can also affect sludge dewaterability and digestate characteristics, although there are few studies on this topic [11]. Some studies suggest enhanced solids dewaterability with co-digestion [42]. Thus, mangers should focus on sustainable approaches to biosolids reuse [11,43] and carefully assess the implications of returning co-digestate to the headworks, a typical digestate disposal strategy in municipal wastewater treatment plants. Another key focus of waste managers should be the diversion or removal of inert material from FW, which can impede the co-digestion process and the subsequent reuse of biosolids [11]. The Park may need to reevaluate the use of "biodegradable" polylactic acid plastic cups and utensils. An initial study conducted on the Park's polylactic acid plastic dining supplies showed a negligible mass loss over a 35-day anaerobic digestion experiment (Beutel and Burmistrova, unpublished), a finding similar to others [44,45]. An additional challenge related to CHP energy recovery is the need for biogas pretreatment for the removal of siloxanes, sulfides, and moisture prior to combustion [10].

The Park produces several additional organic waste products, including horse manure, green waste, and kitchen grease, that could be integrated into future co-digestion and biosolids management efforts at the El Portal wastewater treatment plant [18]. For example, the co-digestion of 550,000 kg/year of horse manure produced at the Park, assuming a specific methane potential of 140 mL CH_4/g VS and a VS content of 0.19 g/g [46], could produce an estimated 15,000 m^3/year of additional methane, which is equivalent to about one-third of the current methane production at the wastewater treatment plant. The waste biomass conversion of lignocellulosic-based green waste into biofuels has the advantage of using a non-edible feed stock rather than more digestible food crops that support human nutrition [47]. However, this organic feedstock requires significant pretreatment, as cellulose and lignin are not biodegradable via typical anaerobic co-digestion processes. Promising novel approaches for lignocellulosic pretreatment include chemical processing with nanomaterials, such as recoverable magnetic nanoparticles coated with hydrolytic enzymes (e.g., cellulases, hemicellulases, cellobiases) [47], and lignin bioconversion using microbial methods including synthetic biology and metabolic engineering [48].

5. Conclusions

Yosemite National Park aims to fully divert solid waste away from landfills over the coming decade. In addition, the Park plans to upgrade its wastewater treatment plant in El Portal, California. To enhance waste management sustainability at the Park, this preliminary study assessed the feasibility of using the anaerobic co-digestion of FW and WWS at the Park's existing treatment plant to divert organic waste from landfills while enhancing energy production by promoting biogas production. A BMP assay using waste from the Park was first used to assess the impact of increasing the amounts of FW relative to WWS on methane production. A higher %FW corresponded with a higher specific methane yield, an elevated biogas methane content, and slower degradation kinetics. The Park produces an estimated 320,000 kg VS/year of FW and 150,000 kg VS/year of WWS (%FW ~70%) that, based on BMP results, could yield ~205,800 m^3/year of methane, with an energy content of ~2,040,800 kWh/year. This is a five-fold increase in biogas production over current operations. Mass loading calculations suggest that this waste could be co-digested in the Park's current anaerobic digester facilities. Combusting methane-rich biogas via CHP would produce considerably more electricity (634,700 kWh/year) than that currently used at the plant and more than enough heat (793,900 kWh/year) to meet digester heating needs. Several issues need to be considered when implementing co-digestion, including the seasonality of feed stocks and energy demand; the pretreatment of FW; changes in solids production, sludge dewaterability, and digestate characteristics; the diversion or removal of inert material from FW; and biogas pretreatment prior to combustion. While challenging, the co-digestion of FW and WSS appears very promising, should be studied further, and should be integrated in the Park's wastewater facility upgrades.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su141911877/s1. Table S1. Experimental design of biochemical methane potential incubations; Table S2. Summary of Park waste characterization and production; Table S3. Summary of biochemical methane potential experimental results; Figure S1. Regression of cumulative specific methane yield and cumulative volumetric methane yield with %FW.

Author Contributions: Conceptualization, M.B. and J.B.; writing—original draft preparation, J.B. and M.B.; writing—review and editing, M.B., J.B., E.H., R.R. and P.P.; laboratory analyses, J.B., R.R. and P.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported in part by a Blum Center 2018–2019 Seed Grant, University of California, Merced.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Applicable data are included in the Supplemental Materials and/or can be requested from the corresponding author.

Acknowledgments: This paper was based on an M.S. thesis by Julia Burmistrova in the Environmental Systems Graduate Group at the University of California, Merced completed in 2019 entitled *Assessment of Anaerobic Co-digestion of Food Waste and Wastewater Solids for Sustainable Waste Management in Yosemite National Park, USA* and includes a significant reassessment of the dataset and new information. We would like to thank the following people for their support during this project: Steve Shackelton, Executive Director, Gallo Management, University of California, Merced and National Park Service Associate Director for Visitor and Resource Protection (retired); Jodi Bailey, sustainability advisor to the National Park Service; George Harders, manager of the El Portal wastewater treatment plant, National Park Service; Sean Bittle, operator at the El Portal wastewater treatment plant, National Park Service; and Stephanie Lansing and Abhinav Choudhury, University of Maryland Environmental Science and Technology Department. The views expressed in this paper are exclusively those of the authors; they do not represent any official policies or positions of the supporting entities.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Odum, H.T. *Environment, Power, and Society for the Twenty-First Century*; Columbia University Press: New York, NY, USA, 2007.
2. Hoornweg, D.; Bhada-Tata, P. *What a Waste: A Global Review of Solid Waste Management*; World Bank: Washington, DC, USA, 2012.
3. Appels, L.; Lauwers, J.; Degrve, J.; Helsen, L.; Lievens, B.; Willems, K.; Van Impe, J.; Dewil, R. Anaerobic Digestion in Global Bio-Energy Production: Potential and Research Challenges. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4295–4301. [CrossRef]
4. Braguglia, C.M.; Gallipoli, A.; Gianico, A.; Pagliaccia, P. Anaerobic Bioconversion of Food Waste into Energy: A Critical Review. *Bioresour. Technol.* **2018**, *248*, 37–56. [CrossRef]
5. McCarty, P.L.; Bae, J.; Kim, J. Domestic Wastewater Treatment as a Net Energy Producer-Can This Be Achieved? *Environ. Sci. Technol.* **2011**, *45*, 7100–7106. [CrossRef] [PubMed]
6. Satchwell, A.J.; Scown, C.D.; Smith, S.J.; Amirebrahimi, J.; Jin, L.; Kirchstetter, T.W.; Brown, N.J.; Preble, C.V. Accelerating the Deployment of Anaerobic Digestion to Meet Zero Waste Goals. *Environ. Sci. Technol.* **2018**, *52*, 13663–13669. [CrossRef] [PubMed]
7. Guven, H.; Ersahin, M.E.; Dereli, R.K.; Ozgun, H.; Isik, I.; Ozturk, I. Energy Recovery Potential of Anaerobic Digestion of Excess Sludge from High-Rate Activated Sludge Systems Co-Treating Municipal Wastewater and Food Waste. *Energy* **2019**, *172*, 1027–1036. [CrossRef]
8. Mehariya, S.; Patel, A.K.; Obulisamy, P.K.; Punniyakotti, E.; Wong, J.W. Co-digestion of food waste and sewage sludge for methane production: Current status and perspective. *Bioresour. Technol.* **2018**, *265*, 519–531. [CrossRef]
9. Tchobanoglous, G.; Stensel, H.D.; Tsuchihashi, R. (Eds.) *Metcalf and Eddy Wastewater Engineering: Treatment and Resource Recovery*, 5th ed.; McGraw Hill Education: New York, NY, USA, 2014.
10. Shen, Y.; Linville, J.L.; Urgun-Demirtas, M.; Mintz, M.M.; Snyder, S.W. An Overview of Biogas Production and Utilization at Full-Scale Wastewater Treatment Plants (WWTPs) in the United States: Challenges and Opportunities towards Energy-Neutral WWTPs. *Renew. Sustain. Energy Rev.* **2015**, *50*, 346–362. [CrossRef]
11. Nghiem, L.D.; Koch, K.; Bolzonella, D.; Drewes, J.E. Full Scale Co-Digestion of Wastewater Sludge and Food Waste: Bottlenecks and Possibilities. *Renew. Sustain. Energy Rev.* **2017**, *72*, 354–362. [CrossRef]
12. Macintosh, C.; Astals, S.; Sembera, C.; Ertl, A.; Drewes, J.E.; Jensen, P.D.; Koch, K. Successful strategies for increasing energy self-sufficiency at Grüneck wastewater treatment plant in Germany by food waste co-digestion and improved aeration. *Appl. Energy* **2019**, *242*, 797–808. [CrossRef]
13. American Society of Civil Engineers (ASCE). *2017 Infrastructure Report Card: Wastewater*; American Society of Civil Engineers: Washington, DC, USA, 2017.
14. Xu, R.; Zhang, K.; Liu, P.; Khan, A.; Xiong, J.; Tian, F.; Li, X. A Critical Review on the Interaction of Substrate Nutrient Balance and Microbial Community Structure and Function in Anaerobic Co-Digestion. *Bioresour. Technol.* **2018**, *247*, 1119–1127. [CrossRef]
15. Powell, J.T.; Townsend, T.G.; Zimmerman, J.B. Estimates of Solid Waste Disposal Rates and Reduction Targets for Landfill Gas Emissions. *Nat. Clim. Chang.* **2016**, *6*, 162–165. [CrossRef]
16. Rasi, S.; Veijanen, A.; Rintala, J. Trace Compounds of Biogas from Different Biogas Production Plants. *Energy* **2007**, *32*, 1375–1380. [CrossRef]
17. Swain, B. Waste to Fuel Program—City of Manteca WQCF. Presentation at the U.C. Merced Biogas Workshop, Merced, CA, USA. Available online: https://ucmerced.app.box.com/v/citrisbiogas2019 (accessed on 12 November 2019).
18. National Park Service (NPS) Zero Landfill Initiative. Available online: https://www.nps.gov/yose/getinvolved/zlf.htm (accessed on 1 December 2019).
19. Moody, L.B.; Burns, R.T.; Bishop, G.; Sell, S.T.; Spajic, R. Using Biochemical Methane Potential Assays to Aid in Co-Substrate Selection for Co-Digestion. *Appl. Eng. Agric.* **2011**, *27*, 433–440. [CrossRef]
20. Raposo, F.; De La Rubia, M.A.; Fernández-Cegrí, V.; Borja, R. Anaerobic Digestion of Solid Organic Substrates in Batch Mode: An Overview Relating to Methane Yields and Experimental Procedures. *Renew. Sustain. Energy Rev.* **2012**, *16*, 861–877. [CrossRef]

21. Montecchio, D.; Astals, S.; Di Castro, V.; Gallipoli, A.; Gianico, A.; Pagliaccia, P.; Piemonte, V.; Rossetti, S.; Tonanzi, B.; Braguglia, C.M. Anaerobic Co-Digestion of Food Waste and Waste Activated Sludge: ADM1 Modelling and Microbial Analysis to Gain Insights into the Two Substrates' Synergistic Effects. *Waste Manag.* **2019**, *97*, 27–37. [CrossRef] [PubMed]
22. Holliger, C.; Alves, M.; Andrade, D.; Angelidaki, I.; Astals, S.; Baier, U.; Bougrier, C.; Buffière, P.; Carballa, M.; De Wilde, V.; et al. Towards a Standardization of Biomethane Potential Tests. *Water Sci. Technol.* **2016**, *74*, 2515–2522. [CrossRef]
23. MidAtlantic Solid Waste Consultants. *Waste Characterization Study, Yosemite National Park*; Draft Report to the National Parks Conservation Association, Washington, DC, USA; MidAtlantic Solid Waste Consultants: Orlando, FL, USA, 2015.
24. American Public Health Association (APHA). *Standard Methods for the Examination of Water and Wastewater*, 21st ed.; American Public Health Association: Washington, DC, USA, 2005.
25. Lisboa, M.S.; Lansing, S. Characterizing Food Waste Substrates for Co-Digestion through Biochemical Methane Potential (BMP) Experiments. *Waste Manag.* **2013**, *33*, 2664–2669. [CrossRef]
26. Sundberg, C.; Franke-Whittle, I.H.; Kauppi, S.; Yu, D.; Romantschuk, M.; Insam, H.; Jönsson, H. Characterization of Source-Separated Household Waste Intended for Composting. *Bioresour. Technol.* **2011**, *102*, 2859–2867. [CrossRef]
27. Holliger, C.; de Laclos, H.F.; Hack, G. Methane Production of Full-Scale Anaerobic Digestion Plants Calculated from Substrate's Biomethane Potentials Compares Well with the One Measured on-Site. *Front. Energy Res.* **2017**, *5*, 1–9. [CrossRef]
28. Zhang, R.; El-Mashad, H.M.; Hartman, K.; Wang, F.; Liu, G.; Choate, C.; Gamble, P. Characterization of Food Waste as Feedstock for Anaerobic Digestion. *Bioresour. Technol.* **2007**, *98*, 929–935. [CrossRef]
29. Kim, H.W.; Han, S.K.; Shin, H.S. The optimization of food waste addition as a co-substrate in anaerobic digestion of sewage sludge. *Waste Manag. Res.* **2003**, *21*, 515–526. [CrossRef] [PubMed]
30. Dai, X.; Duan, N.; Dong, B.; Dai, L. High-Solids Anaerobic Co-Digestion of Sewage Sludge and Food Waste in Comparison with Mono Digestions: Stability and Performance. *Waste Manag.* **2012**, *33*, 308–316. [CrossRef] [PubMed]
31. Gu, J.; Liu, R.; Cheng, Y.; Stanisavljevic, N.; Li, L.; Djatkov, D.; Peng, X.; Wang, X. Anaerobic Co-Digestion of Food Waste and Sewage Sludge under Mesophilic and Thermophilic Conditions: Focusing on Synergistic Effects on Methane Production. *Bioresour. Technol.* **2020**, *301*, 122765. [CrossRef] [PubMed]
32. Sosnowski, P.; Klepacz-Smolka, A.; Kaczorek, K.; Ledakowicz, S. Kinetic investigations of methane co-fermentation of sewage sludge and organic fraction of municipal solid wastes. *Bioresour. Technol.* **2008**, *99*, 5731–5737. [CrossRef] [PubMed]
33. Raposo, F.; Fernández-Cegrí, V.; de la Rubia, M.A.; Borja, R.; Béline, F.; Cavinato, C.; Demirer, G.; Fernández, B.; Fernández-Polanco, M.; Frigon, J.C.; et al. Biochemical Methane Potential (BMP) of Solid Organic Substrates: Evaluation of Anaerobic Biodegradability Using Data from an International Interlaboratory Study. *J. Chem. Technol. Biotechnol.* **2011**, *86*, 1088–1098. [CrossRef]
34. Izumi, K.; Okishio, Y.K.; Nagao, N.; Niwa, C.; Yamamoto, S.; Toda, T. Effects of Particle Size on Anaerobic Digestion of Food Waste. *Int. Biodeterior. Biodegrad.* **2010**, *64*, 601–608. [CrossRef]
35. Prabhu, M.S.; Mutnuri, S. Anaerobic co-digestion of sewage sludge and food waste. *Waste Manag. Res.* **2016**, *34*, 307–315. [CrossRef]
36. Elbeshbishy, E.; Nakhla, G.; Hafez, H. Biochemical Methane Potential (BMP) of Food Waste and Primary Sludge: Influence of Inoculum Pre-Incubation and Inoculum Source. *Bioresour. Technol.* **2012**, *110*, 18–25. [CrossRef]
37. United States Department of Energy (USDOE). *Combined Heat and Power Technology Fact Sheet Series*; United States Department of Energy: Washington, DC, USA, 2017.
38. United States Environmental Protection Agency (USEPA). *Opportunities for Combined Heat and Power at Wastewater Treatment Facilities: Market Analysis and Lessons from the Field*; United States Environmental Protection Agency: Washington, DC, USA, 2014; Volume 2012.
39. Xu, F.; Li, Y.; Ge, X.; Yang, L.; Li, Y. Anaerobic Digestion of Food Waste—Challenges and Opportunities. *Bioresour. Technol.* **2018**, *247*, 1047–1058. [CrossRef]
40. Schievano, A.; Tenca, A.; Scaglia, B.; Merlino, G.; Rizzi, A.; Daffonchio, D.; Oberti, R.; Adani, F. Two-stage vs single-stage thermophilic anaerobic digestion: Comparison of energy production and biodegradation efficiencies. *Environ. Sci. Technol.* **2012**, *46*, 8502–8510. [CrossRef]
41. Baldi, F.; Pecorini, I.; Iannelli, R. Comparison of single-stage and two-stage anaerobic co-digestion of food waste and activated sludge for hydrogen and methane production. *Renew. Energy* **2019**, *143*, 1755–1765. [CrossRef]
42. Karki, R.; Chuenchart, W.; Surendra, K.C.; Shrestha, S.; Raskin, L.; Sung, S.; Hashimoto, A.; Khanal, S.K. Anaerobic co-digestion: Current status and perspectives. *Bioresour. Technol.* **2021**, *330*, 125001. [CrossRef] [PubMed]
43. Joo, S.H.; Dello Monaco, F.; Antmann, E.; Chorath, P. Sustainable Approaches for Minimizing Biosolids Production and Maximizing Reuse Options in Sludge Management: A Review. *J. Environ. Manag.* **2015**, *158*, 133–145. [CrossRef] [PubMed]
44. Benn, N.; Zitomer, D. Pretreatment and Anaerobic Co-Digestion of Selected PHB and PLA Bioplastics. *Front. Environ. Sci.* **2018**, *5*, 1–9. [CrossRef]
45. Krause, M.J.; Townsend, T.G. Life-Cycle Assumptions of Landfilled Polylactic Acid Underpredict Methane Generation. *Environ. Sci. Technol. Lett.* **2016**, *3*, 166–169. [CrossRef]
46. Kafle, G.K.; Chen, L. Comparison on Batch Anaerobic Digestion of Five Different Livestock Manures and Prediction of Biochemical Methane Potential Using Different Statistical Models. *Waste Manag.* **2016**, *48*, 492–502. [CrossRef]

47. Singhvi, M.S.; Kim, B.S. Current developments in lignocellulosic biomass conversion into biofuels using nanobiotechology approach. *Energies* **2020**, *13*, 5300. [CrossRef]
48. Singhvi, M.S.; Kim, B.S. Lignin valorization using biological approach. *Biotechnol. Appl. Biochem.* **2021**, *68*, 459–468. [CrossRef]