Anaerobic Co-Digestion with Food Waste: A Possible Alternative to Overcome the Energy Deficit of Sludge Thermal Pretreatment

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ABSTRACT: Thermal pretreatment (TP) was an effective method to improve the anaerobic digestion of waste-activated sludge. In order to balance the energy consumption of sludge TP integrated with anaerobic digestion, food waste was introduced as a co-substrate to achieve an energy self-sustainable sludge treatment system. An anaerobic biodegradability test was performed using thermal pretreated sludge and food waste in order to clarify the kinetics and mechanism of co-digestion, especially the synergetic effect on specific methane yield. The prominent synergetic effect was an initial acceleration of cumulative methane production by 20.7–23.8% observed during the first 15 days. The modified Gompertz model presented a better agreement of the experimental results, and it was a suitable tool for methane production prediction of mono- and co-digestion. The energy assessment showed that co-digestion with food waste was a sustainable solution. When the moisture content of the TP sludge was 80–90%, the energy compensation required was about 0.04–0.22 t VS Foodwaste/t VS Sludge which could maintain the integration of neutral or even positive energy between TP and anaerobic digestion.

1. INTRODUCTION

Nowadays, waste-activated sludge is globally recognized as a potential resource for renewable energy and nutrient recovery rather than an environmental liability. Anaerobic digestion has proven to be a reliable and economical technology of waste-activated sludge management and is considered as an essential part of modern municipal wastewater treatment plants (WWTPs) to reduce the amount of waste-activated sludge and to recover bioenergy.7,3 Hydrolysis of organic particulates known as the rate-limiting step in sludge anaerobic digestion is limited by cell wall rupture and extracellular polymeric substance degradation.4 To sidestep the bottleneck, various disintegration methods have been introduced prior to anaerobic digestion to release the readily biodegradable substrate contained in the cell.5,6 Thermal pretreatment (TP) is a temperature-dependent reaction, and the maximum methane production is reached at the reaction temperature ranging from 150 to 175 °C.7–9 Several commercial technologies, such as Cambi, Exelys (Veolia), and CTH (Aqualogy), state that TP can integrate in WWTPs with complete energy self-sufficiency.10 With the rapid industrialization and urbanization, at least 6.25 million tons of dry sludge is generated per year from over 3600 WWTPs in China, with a processing capacity of 49.43 billion m³/d, and the sludge production is expected to increase in the near future.11,12 However, the organic particulate in the sewage is removed using a septic tank and is further diluted by storm water or underground water in the pipeline. As a result, waste-activated sludge in China contains only 20–50% of organic content, much lower than that in developed countries, (70–80%).12 The shortage of organics leads directly to a low energy content in the sludge, which has a critical role in the energy generation as biogas produced in anaerobic digestion. In view of the energy balance, TP and anaerobic digestion of waste-activated sludge will stay at their infancy in China until a higher concentration of organic matter is available in the influent of WWTPs.

To solve this problem, anaerobic co-digestion (AcoD) of the high organic feedstock such as food waste (with a methane potential of 302–716 mL CH₄/g VSₘ) is a feasible option to improve the digestion efficiency, stability, and energy benefit.13,14 Astals reported that the synergistic effect in co-digestion led to an acceleration of specific methane yield rather than a significant change in cumulative methane production. The results showed that the benefit of AcoD was enhancing not only methane production but also an acceleration of the degradation kinetics.15 The renewable energy systems (RESs) in Europe have set forward a fixed goal of supplying 20% of the

Received: June 14, 2022
Accepted: October 14, 2022
Published: October 24, 2022
European energy demands from RESs by 2020, and at least 25% of the bioenergy in the future can originate from biogas produced from wet organic materials such as animal manure, whole crop silages, wet food, feed wastes, and so on. America has also harnessed biogas from organic waste management since at least the 1920s, and feeding fat, oil, and grease to digesters presented better economic benefits. In practice, AcoD with food waste (FW) is a cost-effective alternative to improve the energy balance of sludge treatment systems. However, few studies have evaluated the synergetic effect and the energy balance of AcoD integrated with sludge TP. Liu et al. applied TP to accelerate FW solubilization before co-digestion with waste-activated sludge. However, Cano et al. suggested that TP had not showed remarkable effect on easily degradable substances rich in lipids and carbohydrates. Besides, Cueto et al. reported the instability and inhibition in an mesophilic AcoD of thermal pretreated slaughterhouse waste (at 133 °C for 20 min) caused by long-chain fatty acid (LCFA) accumulation. Thus, TP of the easily biodegradable substrates prior to AcoD seems contradictory to its original intention.

Until now, the effects of TP of waste-activated sludge on methane production and kinetics parameters were widely studied and the synergetic effects and mechanism of co-digestion were generally discussed. Nonetheless, the synergetic effects of co-digestion of thermal pretreated sludge (TPS) and FW need to be evaluated, and an available tool is required to assess the energy feasibility of full-scale applications and set the basis of process control.

Therefore, the primary objective of this study was to provide better insights into the synergetic effects of TPS and FW in anaerobic digestion. The modified Gompertz model and first-order model were used to analyze the experimental data and to predict the performance of co-digestion. From them, an energy assessment was performed by analysis energy consumption of the seven different solid contents of waste-activated sludge in TP to evaluate the feasibility to maintain an energy self-sustained AcoD system integrated with the sludge TP process.

2. MATERIALS AND METHODS

2.1. Substrates and Inoculum. Press cake of wasted-activated sludge from the municipal WWTWs (Nanning, China), with a capacity of 4.8 × 10^5 m^3/d using a reverse anoxic–anaerobic–aerobic process, was diluted to 10% of total solid (TS) with distilled water before homogenizing (WBL25B26, Midea Co., Ltd., China), and then the sludge slurry was stored at 4 °C.

FW from Guangxi University canteen was used in this study. Non-biodegradable material such as bones, plastic, and glass was removed manually before homogenization. FW slurry was packed in a plastic container and stored at 4 °C. FW slurry was thawed to ambient temperature before feeding.

Inoculum from a pilot-scale anaerobic digester fed with pretreated sludge was sieved through a 1 mm mesh to remove large particles. Inoculum used in this test was degassed by incubation at 37 °C until no significant methane production was observed.

2.2. Thermal Pretreatment. TP was conducted using an electric-heating reactor (HK-ZZ01, Hengke Instruments, China) equipped with four 1 L hydrothermal synthesis reactors inside the chamber. Homogenized sludge slurry was treated at 165 °C for 15 min. Pretreated sludge was stored at 4 °C for further analysis and tests.

2.3. Anaerobic Biodegradability Test. Anaerobic biodegradability tests were conducted to evaluate the biodegradability of the mono-substrates (pure sludge without thermal pretreatment and FW addition (WAS), TPS, and FW) and three mixtures (TPS/FW = 64%/36%, 37%/63%, and 17%/87%, named as AcoD-I, -II, and -III) in triplicate.

All the experiments were carried out with the feeding/inoculum ratio (0.5 g of VSFeed/g VSIno) suggested by Angelidaki. The head space of the 500 mL serum bottle, used as bench-scale digester, was flushed with nitrogen for 3 min before sealing with rubber stoppers. The digesters were immersed in a water batch at 37 ± 0.5 °C and manually mixed on a daily basis. Daily methane yield was measured by the liquid displacement method with 2% NaOH solution. All tests were performed in triplicate, and methane production was normalized to the volatile solid (VS) in the substrate.

Specific methane yield and cumulative methane production were calculated in VS-base. Although the so-called 1% criterion was adopted, the ultimate methane production obtained in this study was not equivalent to the biochemical methane potential of the substrate.

2.4. Analytical Methods. In order to know the dilution factor of the sludge press cake and FW, TS and VS of all the samples were determined by heating at 105 °C for 24 h for TSs and 550 °C for 2 h for VSs. Soluble fractions of the sludge were defined by centrifuging at 8000 rpm for 20 min, and the supernatants were characterized by soluble chemical oxygen demand (SCOD), ammonia, alkalinity, and volatile fatty acids (VFAs) (Table 1). VFA was analyzed according to the five-point titration method. The content of ammonia nitrogen was determined by ultraviolet spectrophotometry with an NF reagent. SCOD, TS, VS, pH, and alkalinity were determined according to standard methods. All analyses were performed in triplicate and given as mean ± standard deviation.

2.5. Calculation. 2.5.1. Modeling. The objective of introducing the simplified models was to obtain kinetics parameters, allowing us to compare the results and predict the methane production. The modified Gompertz model and first-order model were applied to estimate the kinetics parameter in this work, allowing reliable comparison between mono- and co-digestion. Nonlinear optimization by the least squares procedure was applied in the simulation using Matlab (R2014a).

The modified Gompertz model, next presented in eq 1, was used to describe the progression of cumulative methane production in the batch tests.

\[ M = M_0 \exp \left\{ -\exp \left( \frac{R_{\text{max}} \cdot (\lambda - t)}{M_0} \right) + 1 \right\} \]

Table 1. Characteristics of Raw Sludge, TPS, and FW

|                          | raw sludge | TPS      | FW       |
|--------------------------|------------|----------|----------|
| TS (%, ww)               | 21.6 ± 0.2 | 10.0 ± 0.4 | 13.6 ± 0.2 |
| VS/TS (%)                | 54.7 ± 0.3 | 52.4 ± 0.3 | 91.9 ± 0.2 |
| SCOD (mg/L)              | 2870 ± 150 | 18830 ± 530 | 10750 ± 330 |
| pH                       | 8.2 ± 0.1  | 5.8 ± 0.1  | 4.8 ± 0.1  |
| VFA (mg/L)               | 330 ± 14   | 2470 ± 210 | 1850 ± 170 |
| alkalinity (mg/L)        | 645 ± 30   | 1250 ± 135 | 580 ± 23   |
| total ammonia nitrogen   | 36 ± 7     | 415 ± 13   | 103 ± 17   |
| (mg/L)                   |            |           |           |
Figure 1. Cumulative methane production in the anaerobic biodegradability tests using mono- and co-substrates. Experimental data (dotted line), model fit (solid line), and two model-base estimation (dashed line).
where $M$ is the cumulative methane production (mL CH$_4$/g VS$_{in}$), $M_0$ is the ultimate methane production (mL CH$_4$/g VS$_{in}$), $R_{max}$ is the ultimate specific methane production rate (mL CH$_4$/g VS$_{in}$·d), $\lambda$ is the lag phase time (day), $t$ is the digestion time (day), and $e \approx 2.718$.

First-order kinetics is used to describe the hydrolysis of particulate organic matter. The progression of cumulative methane production can be described by the following equation.

$$M(t) = M_0 \times [1 - \exp(-k_h t)]$$

where $M(t)$ is the cumulative methane potential (mL CH$_4$/g VS$_{in}$) at digestion time $t$ days, $M_0$ is the ultimate methane potential of the substrate mL CH$_4$/g VS$_{in}$·d, $k_h$ is the first-order hydrolysis rate constant (d$^{-1}$), and $t$ is the digestion time (days).

2.5.2. Theoretical Methane Production. The term “methane production” can refer to cumulative methane production (mL CH$_4$/g VS$_{in}$) or specific methane yield (mL CH$_4$/g VS$_{in}$·d) in this study. If the type and the composition of the substrate are known and all the materials are converted to biogas, the theoretical methane production of the substrate can be calculated from the following equation.$^{15,34}$

$$M_T(t) = p \times M_{TPS} + (1 - p) \times M_{FW}$$

where $M_T(t)$ is the theoretical methane production of the mixture fed in AcoD, $M_{TPS}$ and $M_{FW}$ are the methane production of TPS and FW in mono-substrate digestion, and $p$ (%) is the organic fraction of pretreated sludge in the mixture.

2.5.3. Relative Deviation. The synergistic effect during co-digestion was expressed as the relative deviation of theoretical production to quantify the difference between mono-substrate digestion and co-digestion from the following equation

$$RD(\%) = \frac{(M - M_T)}{M_T} \times 100\%$$

where RD (%) is the relative deviation of the experimental data and the theoretical estimation of cumulative methane production, $M$ (mL CH$_4$/g VS$_{in}$) is the cumulative methane production of co-digestion, or its fitted value of the kinetics model, and $M_T$ (mL CH$_4$/g VS$_{in}$) is its theoretical cumulative methane production calculated by eq 3.

2.6. Energy Assessment. The cumulative methane production and specific methane yield of the substrate in a specified period were recorded by sequential batch anaerobic fermentation. The average temperature and time of TP is 170 °C and 30 min, and dehydrated sludge (TS, 16%) is added.$^{21}$ The thermal hydrolysis time starts from the time when the temperature in the cooking pot reaches the predetermined temperature. Methane production expressed per ton of VS feed.

Figure 2. Specific methane yield of raw sludge (Raw), TPS, and FW (experimental data, black solid line; and theoretical estimation, red dotted line).
was used for energy assessment. The activated sludge has different moisture contents by using belt filter press and folding requirement per ton of sludge (by wet weight) is 18.7 Nm³ heating is generated in a boiler supplied with biogas. The energy calculated. For the simplest TP scheme, the steam required for production of FW calculated on TS basis would stretch to 7.49.

3. RESULTS AND DISCUSSION

3.1. Anaerobic Biodegradability Test. 3.1.1. Cumulative Methane Production. Cumulative methane production of waste-activated sludge increased by 57% after pretreatment, from 197 mL of CH₄/g VSₘ₀ to 310 mL of CH₄/g VSₘ₀. It was evidenced that TP improved the biodegradability of waste-activated sludge and unlocked its potential, unable to release in anaerobic digestion without pretreatment. Cano reported a similar result that methane production increased from 184 mL of CH₄/g VSₘ₀ for raw sludge to 278 mL of CH₄/g VSₘ₀ for the treated sludge. The maximum cumulative methane production (819 mL of CH₄/g VSₘ₀) was obtained from FW, which was 1.64 and 3.16 times that of raw sludge and treated sludge. Considering the organic content (92.0% for FW and only 54.7% for RS), the actual multiples of cumulative methane production of FW calculated on TS basis would stretch to 7.49 and 4.95 times that for raw sludge and treated sludge, in accordance with El-Mashad and Zhang. This result suggested that FW is a reasonable co-substrate to improve the energy balance of the anaerobic digestion process integrated with TP and/or a combined heat and power system.

As shown in Figures 1 and 2, co-digestion exerted a greater effect on the maximum specific methane yield than cumulative methane production. Theoretical cumulative methane production of co-digestion calculated from eq 3 agreed with the deviation of the theoretical calculations in all tests fell below 10% after 15 days, the suggested solid retention time for completely mixed mesophilic digesters. In the end, the relative deviation was down to 1.5%, indicating that the ultimate cumulative methane production of the substrates was conserved and determined by the substrate composition. Astals also reported that the synergistic effect in co-digestion led to an acceleration of specific methane yield rather than a significant change in cumulative methane production.

3.1.2. Specific Methane Yield. Specific methane yield of mono-substrates (FW, TPS, and raw sludge) demonstrated the different degradation kinetics in anaerobic digestion (Figure 2). Pretreated sludge started with a rapid spike of 46 mL of CH₄/g VSₘ₀ at day 3, followed by a moderate decrease since day 8, whereas that of raw sludge remained fairly constant below 15 mL of CH₄/g VSₘ₀ throughout the experiment. The rapid methane production observed in the early phase was attributed to the liberation of the intra-cellular content from waste-activated sludge, thus providing more accessible soluble and micro-particle organics for the anaerobic microorganism. This assumption was supported by the remarkable enhancement of SCOD and VFAs due to the cell breakage and intercellular substrate leakage in accordance with Mottet et al. Besides the solubilization, the deflocculation of the macro-flocs structure in pretreatment provided extra surface area for microorganisms.

The specific methane yield of FW fitted a sawtooth profile with three major peaks of 57, 45, and 56 mL of CH₄/g VSₘ₀ at days 2, 7, and 12, suggesting that as a mixture of multi-substrate, FW would show a complex degradation behavior as the result of the combined effect of particle size distribution and chemical composition.

Specific methane yields in co-digestions (solid line, black) along with their theoretical estimations (dotted line, red) calculated according to eq 3 are shown in Figure 2. By summing the specific methane yield of each substrate, the superposition of the signature curve shape was obtained. As expected, the signature three-peak curve of FW observed in mono-substrate digestion reappeared in AcoD-II and AcoD-III, which had higher weight of FW in the mixture.

However, the prominent feature of the synergistic effect of co-digestion was the acceleration of specific methane yield observed in the first 10 days for all co-digestion tests. This difference between experimental data and theoretical prediction might be associated with the inhibitory compound’s dilution. For example, LCFAs, the intermediates of lipid degradation, were known as an inhibitor for Gram-positive bacteria even at low concentrations. The toxicity of LCFAs was caused by the surface adsorption on the cell wall or cell membrane, which resulted in the malfunction of mass transfer and/or cell protection. In the test, the addition of TPS diluted the LCFA concentration in the digestor, thus reducing the probability of inhibition, and improved the digestion efficiency. Due to the conservation of methane potential in co-digestion, the specific methane yield recorded in the experiment inevitably fell below its theoretical estimation after the initial quick methane production, indicating the rapid depletion of organic material.

3.2. Modeling. The results obtained in anaerobic biodegradability tests with the modified Gompertz model and first-order kinetics have been listed in Table 2. The correlation between the experimental and theoretical values is evidenced by the R² values ranging from 0.974 to 0.999. The model selection was then performed statistically according to the R² values and the chi-squared goodness of fit test, which is calculated as follows:

\[ \chi^2 = \frac{\sum \left( \frac{\text{Experimental} - \text{Theoretical}}{\text{Standard Deviation}} \right)^2}{n} \]

where n is the number of data points. The R² values range from 0.974 to 0.999, indicating a good fit between the model and the experimental data. The chi-squared goodness of fit test indicated that the modified Gompertz model is the most suitable model for the experimental data.

### Table 2. Experimental Data and the Kinetic Parameters Obtained with the Evaluated Models

| Substrate | Experimental | Modified Gompertz Model | First-order Kinetics |
|-----------|--------------|-------------------------|----------------------|
|           | M (mL CH4/g VS) | Rmax (mL CH4/g VS per d) | M0 (mL CH4/g VS) | Rmax (mL CH4/g VS per d) | A | D | R² | M0 (mL CH4/g VS) | kₘ (d⁻¹) | R² |
| Raw Sludge | 197 | 13.6 | 194 | 9.03 | 0.01 | 0.985 | 259 | 0.04 | 0.990 |
| TPS | 310 | 45.8 | 293 | 27.43 | 0.00 | 0.974 | 305 | 0.14 | 0.996 |
| 64% TPS-36% FW | 485 | 59.9 | 463 | 51.97 | 0.64 | 0.988 | 479 | 0.16 | 0.995 |
| 37% TPS-64% FW | 621 | 64.8 | 601 | 56.94 | 1.13 | 0.995 | 619 | 0.14 | 0.995 |
| 17% TPS-83% FW | 731 | 69.2 | 711 | 61.12 | 1.24 | 0.997 | 742 | 0.12 | 0.997 |
| FW | 819 | 56.7 | 846 | 50.69 | 1.86 | 0.999 | 1195 | 0.04 | 0.974 |
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The first-order kinetics (dashed line).

Figure 3. Relative deviation of theoretical methane production obtained with experimental data (solid line), reaction curve model (dotted line), and the first-order kinetics (dashed line).

order kinetics fine-tuning for FW, raw sludge, pretreated sludge, and the mixture are presented in Table 2 and the cumulative methane yield curves are shown in Figure 1. Parameters obtained by both models with a degree of accuracy ($R^2$ over 0.974) enable a quantification of these kinetics improvements (Table 2).

The modified Gompertz model uses three parameters to describe cumulative methane production: ultimate methane production ($M_\text{max}$), ultimate specific methane yield ($R_\text{max}$), and lag phase time ($\lambda$). The ultimate methane potential ($M_\text{max}$) estimated by the modified Gompertz model generally agreed with the experimental results with a negative deviation of 1.5~6.0%. $R_\text{max}$ indicates the initial slope of the curve, describing the maximum daily methane production. Waste-activated sludge suffered an increase of $R_\text{max}$ by 204% after pretreatment, from 9.03 to 27.43 mL of CH$_4$/g VS$_\text{m}$·d, pointing to the deloiculation and the solubilization of sludge flocs.$^{39}$ The $R_\text{max}$ of AcoD-II and AcoD-III were higher than that of FW, which has the highest biochemical methane potential in the test. This result could be explained by two synergetic effects as the result of the TPS addition: (1) supplying extra buffer capacity of VFAs formed in acidogenesis and acetogenesis;$^{40}$ (2) the dilution of LCFA generated in lipid degradation to reduce the risk of inoculum deactivation caused by surface absorption.$^{41}$

The negligible lag time ($\lambda$) of raw sludge and TPS indicated that no significant incubation time was needed for the inoculum to start the digestion process. It is worth considering the potential inhibition caused by the metabolites of protein, grease, and lipid of FW, characterized as a readily biodegradable substrate with high methane potential.$^{42}$ As shown in Table 2, a high proportion of FW in the feed would exert a negative impact on lag time, which could be explained by the depression of inoculum bioactivity caused by LCFA even in low concentrations.$^{39}$

For the first-order model, the apparent hydrolysis constant ($k_1$) is the reciprocal of time when half of the ultimate methane production was achieved. In the case of the TP effect, the initial kinetics acceleration of waste-activated sludge ($k_1$ increased from 0.04 d$^{-1}$ to 0.14 d$^{-1}$) demonstrated the different degradation kinetics of the particulate organic matter and the soluble organic matter, which coincided with the increment of SCOD and VFAs. The hydrolysis constant did not show a clear correlation with the substrate composition like it did with cumulative methane production. However, the comparison between the hydrolysis constant of FW and AcoD-III (17%TPS-83%FW) highlighted the synergetic effect of AcoD, wherein the degradation rate of FW was apparently enhanced by the addition of pretreated sludge (Table 2). As previously discussed, the high proportion of FW fed in the co-digestion would cause temporary inhibitory effects by LCFA absorption and/or VFA accumulation, thus suppressing the bioactivity of the inoculum and slowing down the specific methane yield.

According to the square deviation (Table 2), both models seemed to give a better estimation of cumulative methane production in most cases, and similar results were obtained by Donoso-Brañol$^{43}$ however, the cumulative methane productions of raw sludge and FW were obviously distorted by first-order kinetics in this study. Referring to the lag phase in the modified Gompertz model, the both substrates were slowly biodegradable, which means that they required a longer digestion period to obtain a satisfactory estimation by first-order kinetics. Besides, the modified Gompertz model was superior to the first-order model in describing the curve shape of cumulative methane production, as it can be seen in Figure 1 (solid, line). Up to this point, the comparison between the models was still inconclusive, and more quantitative evidence was necessary to perform further assessment.

3.3. Synergetic Effect Assessment. Supposing there was no interaction between TPS and FW, the RD value shall be null in co-digestion tests. However, before the materials were fully converted, the deviation on the prediction of cumulative methane production reflects the interaction between pretreated sludge and FW in co-digestion. Therefore, the relative deviation of the theoretical estimation was used to quantify the synergetic effect between the co-substrates. According to the experimental results, the synergetic effects was 10.7, 16.0, and 31.2% of improvement for AcoD-I, -II, and -III at the very beginning (Figure 3, solid line). During the first 15 days, the AcoD tests obtained a remarkable increment of cumulative methane production from 20.7 to 23.8%. However, with the depletion of the substrate, the synergetic effect faded away as the co-digestion proceeded, declining from approximately 10% at day 15 to below 1.5% by the end of the experiment. It was interesting to highlight that a small amount of thermal pretreat sludge in AcoD-III would remarkably improve the performance of FW digestion, which might relate to the dilution of the inhabitant previously discussed. In addition, no antagonistic effect was detected in trails of all tested blending ratios.

For a full-scale biogas plant, it is essential to predict the cumulative methane production based on the amount and the composition of the substrates. Theoretically, this estimation could be calculated from eq 3 based on the kinetics model of...
Table 3. Energy Assessment of Anaerobic Co-Digestion Integrated with Sludge TP

| process               | parameter          | unit       | 10%   | 12%   | 14%   | 16%   | 18%   | 20%   | 26%   |
|-----------------------|--------------------|------------|-------|-------|-------|-------|-------|-------|-------|
| TP                    | energy demand      | Nm³/t VS₀Fred | 294.3 | 245.3 | 210.2 | 184.0 | 163.5 | 147.2 | 113.0 |
| anaerobic digestion   | net benefit⁴       | Nm³/t VS₀Fred | 113   | 113   | 113   | 113   | 113   | 113   | 113   |
| AcoD                  | energy gap         | Nm³/t VS₀Fred | −181.3| −132.3| −97.2 | −71.0 | −50.5 | −34.2 | 0.0   |
| FW                   | blend ratio        | t VS₀costrate/t VS₀Sludge | 0.22  | 0.16  | 0.12  | 0.09  | 0.06  | 0.04  |       |

⁴Growth of methane production after TP based on the experimental data in Table 2.

4. CONCLUSIONS

TP led to an increase of cumulative methane production by 57%, equivalent to a net energy benefit of 113 Nm³/t VS₀Fred and kinetics acceleration. The dominant synergetic effect of co-digestion was the acceleration of methane production observed at the early phase, measured with relative deviation by up to 20.7–23.8%.

Both the modified Gompertz model and the first-order kinetics model were capable of evaluating the ultimate cumulative methane production according to the composition of the feedstock. However, the modified Gompertz model provided a more reliable prediction of methane production throughout AcoD owing to its kinetics parameters (lag phase, λ) that enable to fine tune the fitting of the lag phase and synergetic effect witnessed at the start.

The energy balance of the integration of TP and anaerobic digestion was dependent on the methane production of the substrates and the performance of sludge dewatering. FW was highlighted in the energy assessment as an appropriate cosubstrate in co-digestion to improve the energy benefit, especially to neutralize the energy demand in TP. The conclusions in this study shall be verified in continuous experiments before using as a reference in full-scale application to identify the long-term effects of FW on digestion stability.

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Notes

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ACKNOWLEDGMENTS

The authors want to thank China Postdoctoral Science Foundation (2019M663869XB), Guangxi Ba-Gui Scholars Program (2019A33), and Guangxi Natural Science Foundation (2019GXNSFAA185019) for the financial support to this research.

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