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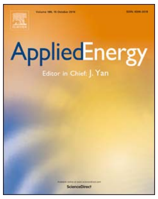

Kinetic studies on organic degradation and its impacts on improving methane production during anaerobic digestion of food waste

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HIGHLIGHTS

- Kinetic parameters of organics degradation were studied using five models.
- Exponential model fits organics reduction data and describe methane yield best.
- Modified Gompertz model better described the lag time than Transference model.
- Interaction of organics reduction and their impact on methane yield were studied.
- Strategies for improving methane yield from food waste digestion were suggested.

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ABSTRACT

Organics degradation is vital for food waste anaerobic digestion performance, however, the influence of organics degradation on biomethane production process has not been fully understood. This study aims to thoroughly investigate the organics degradation performance and identify the interaction between the reduction of organic components and methane yield based on the evaluation on 12 types of food waste. Five models (i.e. exponential, Fitzhugh, transference function, Cone and modified Gompertz models) were compared regarding the prediction of organic degradation and the results showed that the exponential model fit the experiments best, whereas kinetic parameters could not be commonly used for all situations. The exponential model was then used to study the impacts of organics reduction on the methane production and results revealed that the cumulative methane production (385–627 mL/g volatile solid) increased exponentially with the removal efficiency of volatile solids, lipids, and proteins for all feedstocks, whereas volatile solid reduction increased exponentially and linearly, respectively, with the removal efficiency of lipids and proteins. Additionally, protein degradation increased exponentially with the reduction efficiency of lipids. The experimental data and model simulation results suggested that higher methane production (530–548 mL/g volatile solid) and removal efficiency of volatile solids (65.0–67.8%), lipids (77.8–78.2%), and proteins (54.7–58.2%) could be achieved in a shorter digestion retention when carbohydrate content was higher than 47.6%, protein content lower than 24.1%, and lipid content lower than 28.3%.

1. Introduction

Anaerobic digestion of food waste is attracting more and more attention worldwide for recovering energy and reducing greenhouse gas emissions [1,2]. There have been many studies focused on the effect of operating parameters on methane yields, such as operation mode (batch or continuous), temperature (mesophilic or thermophilic), moisture content (wet or dry), organic loading rate, presence or absence of co-substrates (co- or mono-digestion) and hydraulic retention time [3–6]. Furthermore, in order to increase digestion efficiency and improve the methane yield, anaerobic biodegradability of food waste in two-stage [7] and three-stage [8] anaerobic digesters have also been studied, and various pretreatment methods [6,9,10] have been proposed. The energy ratio and economic feasibility were also conducted [9].

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Meanwhile, to allow the prediction of kinetic parameters and to help elucidate the digestion process, some kinetic models have been proposed to describe the process of substrate degradation and biogas production. Simplified generalized models based on first order models have predominantly been employed for parameter estimation, improving the understanding of the biological process and aiding in predicting the behaviour of biological system when designing anaerobic system [11]. It was concluded that kinetic parameters, such as those of biogas production and methane yield, may vary when different models and substrates were used [12]. Li et al. [13] compared three kinetics models, including first-order kinetics, the transfer function model and the cone model for different livestock manures as feedstocks and with different substrate concentrations. The results showed that the cone model had better performance than the first-order and the transfer function models. Kafle and Kim [14] compared the modified Gompertz and first-order kinetics models and showed that, better fitting result was found for the modified Gompertz model. El-Mashad [15] observed that the Cone model best described the cumulative biogas production data, whereas the exponential model was the worst predictor of the experimental data. Moreover, due to the structural and numerical complexity, many models cannot be applied for automatic monitoring or robust simulation of different substrates and process conditions [16]. It is important to highlight that previous studies devoted to the kinetic parameters during digestion of food waste were simplified to focus on fitting the experimental data of biogas/methane production [10], and very few studies centred on the detailed kinetic degradation properties of organics in food waste (i.e. volatile solids, total solids, lipids and proteins) and their correlations during the anaerobic digestion of food waste. Additionally, food waste can present important differences as the composition can vary with factors such as food availability, seasonal variation and consumption patterns. For food waste, lipids are one of the main organic components and may have a bi-directional effect on digestion [17]. However, calculation of the hydrolysis constant using kinetic models from the previous study was only made for a combined fraction of carbohydrates and proteins, omitting the lipid fraction [18]. Moreover, Miron et al. [18] suggested that the hydrolysis constant value might not be a universal constant, as it is no more than a specific calculation for a given substrate under certain conditions. However, it could be noted that previous studies devoted to the kinetic parameters during digestion of food waste (including mono- and co-digestion) were confined to using collected food waste with limited composition ranges [19] and co-digestion with other organic waste (such as dairy manure [20] and sewage sludge [21]).

Therefore, there is a need to extend kinetic models to organics reduction and verify whether kinetic parameters meet this important assumption. Thus, it is necessary to make comparisons of these kinetics models (i.e. the exponential, Fitzhugh, Cone, transference function and modified Gompertz models), which were used to determine the methane production potential, maximum methane production rate and lag time for anaerobic digestion by fitting the measured methane yields [13,16,22–27], and find the appropriate one by model validation for parameter estimation. To further increase the digestion efficiency and improve the biomethane production, making the overall process more energy sustainable, the interaction of organics degradation and their impact on methane production should be studied.

The objectives of this paper are to investigate the degradation performance of organics (i.e. total solids, volatile solids, lipids, and proteins) and maximize the methane yield of food waste by optimizing organics degradation during food waste digestion. This work contributes to improvement the understanding of: (a) the applicability and validation of five simplified and widely applied models for predicting biomethane production performance; and (b) the correlation between the organics reduction in terms of volatile solids, proteins and lipids in food waste. Finally, the optimizations for enhancing biomethane production through the improvement of organic degradation were suggested.

Table 1a
Compositions and characteristics of the three food waste samples.

Parameters	Food waste-1	Food waste-2	Food waste-3
pH	4.5 ± 0.2	5.2 ± 0.0	5.0 ± 0.2
Total solid (%)	19.1 ± 1.1	26.2 ± 0.4	12.7 ± 0.7
Volatile solid (% total solid)	93.2 ± 1.4	94.8 ± 0.5	95.4 ± 1.2
Carbohydrate (%)	11.8 ± 0.4	10.3 ± 0.3	36 ± 2.5
Protein (%)	2.5 ± 0.2	6.3 ± 0.5	41.5 ± 1.8
Lipid (%)	3.5 ± 0.1	8.2 ± 0.2	18.5 ± 0.4
C (% total solid)	46.1 ± 1.6	52.2 ± 1.4	51.5 ± 0.6
H (% total solid)	7.0 ± 0.2	5.4 ± 0.6	7.5 ± 0.3
O (% total solid)	37.8 ± 1.6	32.0 ± 0.4	32.8 ± 0.7
N (%total solid)	3.2 ± 0.4	4.0 ± 0.1	5.3 ± 0.2

2. Materials and methods

2.1. Food waste

Food waste was collected from three different canteens. Impurities, such as big bones, plastics, and metals were manually removed from the food waste. Samples collected from the same canteen were mixed with a kitchen blender to ensure uniform and representative experimental materials. The mixed samples were then macerated to an average size of 1–2 mm. All samples were stored at 4 °C in a refrigerator for the subsequent experiments. The basic compositions and characteristics of the three kinds of food waste used in this experiment are listed in Table 1a.

The ranges of variation of food waste compositions were obtained from a literature review and measurements of samples from 5 typical Chinese cities (e.g. Beijing in North China; Jiaxing in Zhejiang province, East China; Xining in Qinghai province, Northwest China; Qingdao in Shandong province, coastal East China and Guiyang in Guizhou province, South China). A total of 12 different types of food waste with different carbohydrate: protein: lipid ratios were then formed by mixing the three kinds of food waste samples with different ratios, as shown in Table 1b.

The pH was measured using a pH meter (FE 20, Mettler, Switzerland). Total solids, volatile solids and concentrations of total ammonia nitrogen were determined according to the standard methods from the American Public Health Association [28]. The concentration of carbohydrates was analysed according to official methods [29]. The concentrations of proteins and lipids were determined according to the Kjeldahl method and using a Soxhlet device extracted by petroleum ether, respectively [30,31]. Methane production was determined using real-time methane yield recording systems (automatic methane potential test system II). The contents of C, H and N were analysed by CHN Elemental Analysers (CE-440 elemental analyser (EAI Co. Ltd)) and O content was investigated with a PerkinElmer 2400 analyser.

2.2. Anaerobic digestion

Batch digestion tests were conducted at 37 °C by using an automatic methane potential test system II developed by Bioprocess Control (Lund, Sweden). The feed and inoculums were placed into bottles with a feed to inoculums ratio of 1:2 on a volatile solid basis. Seed sludge was obtained from a steady-operation digester (37 °C) in a food waste treatment plant in Beijing, China. After a two-day gravity sedimentation period, the inoculum was passed through a 2 mm sieve to remove any large particles or grit to arrive at total solid and volatile solid contents of 3.65% and 2.42%, respectively, whereas the pH value was 7.34 before mixing with the food waste. The upper space of each reactor was flushed with nitrogen for at least 1 min to guarantee anaerobic conditions before the reactor was sealed. Then, all of the reactors were placed in the digestion system water bath and maintained at a mesophilic temperature (37 °C). For each experimental run, three control digesters were operated. Simultaneously, two blank digesters containing only