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Effects of thermal pretreatment on the biomethane yield and hydrolysis rate of kitchen waste

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HIGHLIGHTS

- Thermal pretreatment had varying impacts on anaerobic digestion.
- Expanded research scope and comprehensive conclusions are obtained.
- Characteristics of digestion kinetic are pretreatment temperature dependent.
- Thermal treatment temperature is recommended to be less than 120 °C.

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ABSTRACT

In this study, batch tests were performed to evaluate the effects of different thermal pretreatment temperatures (55–160 °C) and durations (15–120 min) on the anaerobic digestion of kitchen waste (KW). Two commonly used approaches, namely the modified Gompertz model and the approach developed by Koch and Drewes, were applied to assess the effects of the different pretreatment parameters on the biomethane yield, lag time and hydrolysis rate constant via data fitting. The subsequent anaerobic digestion of KW pretreated at 55–120 °C presented greater efficiency, and longer treatment durations resulted in increased methane production and higher hydrolysis rate constants. These findings were obtained due to the lower nutrient loss observed in KW treated at lower temperature treatments compared with that found with higher temperature treatments. In general, the effects of thermal pretreatment on the lag phase and hydrolysis rate differed depending on the treatment parameters leading to the variations in the KW compositions. The soundness of the two model results was evaluated, and higher statistical indicators (R^2) were found with the modified Gompertz model than with the approach developed by Koch and Drewes.

1. Introduction

With the rapid growth of urban populations and changes in consumption patterns, kitchen waste (KW) has become a major global issue. More than 30 million tons of KW are produced in China every year. This volume of waste creates a number of challenges in terms of environmental protection and public health and represents a tremendous amount of utilizable biomass.

The high biodegradability and water content of KW makes it a good candidate for anaerobic digestion (AD) with the concomitant benefit of biogas production. This process is an acceptable solution for waste management due to its low cost, low production of residual waste and its utilization as a renewable energy source [1–3]. Additionally, the resulting nutrient-rich digestate can also be used as a fertilizer or soil conditioner [2]. AD could provide an opportunity to recycle KW while producing renewable energy, thus attracting increasing attention. In addition, the Renewable Energy directive (2009/28/EC) and the Landfill directive (99/31/EC) have also strongly promoted the use of anaerobic digestion for the disposal of KW in recent years [4,5]. Moreover, four ministries in China (Chinese National Development and Reform Commission, Ministry of Housing and Urban–Rural Development, Ministry of Environmental Protection and Ministry of Agriculture) have co-issued the notification of carrying out the pilot projects on resource utilization and innocuity treatment of KW, and till now 100 pilot projects have been conducted overall planning and combinational optimization to enhance resource-oriented utilization and harmless treatment of KW (FAGAIHUANZI [2010] No. 1020).

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Among these pilot projects, more than 80% chose anaerobic digestion as the primary treatment technique. However, most of them are facing various difficulties, such as unbalanced fermentation, long hydraulic retention time, low biogas yield and methane concentration.

A number of factors may affect biogas production and stability of the AD process, including the inhibitory effects of AD byproducts (e.g., ammonia nitrogen and volatile fatty acids) as well as the physical and chemical characteristics of the waste (such as moisture, volatile solids, nutrient content, particle size and lipid content) [6–8]. Additionally, the long retention time of the AD process is a major concern [9]. KW also has a high lipid content, ranging from 2% to 3% (wet basis), indicating that KW presents a higher biochemical methane potential than other types of organic matter [10]. Nevertheless, the negative effects become more prominent as the lipid concentration increases due to the low degradation rate, leading to the accumulation of intermediate products and undermining the stability and continuity of the methane production process [9–12]. The use of KW for AD presents major limitations because of its rapid acidification, which stresses and inhibits the activity of methanogens [13,14]. Pretreatment is a fundamental step for improving the substrate characteristics in order to achieve improved anaerobic digestion yields. To this end, a large number of pretreatment options, including ultrasonic, thermal, microwave, chemical, electrical and freeze/thaw methods, exist [2,15–17]. The effects of various pretreatment methods are highly different depending on the characteristics of the substrates and the pretreatment type [18]. Among these methods, thermal treatment is one of the most studied pretreatment methods and has been successfully applied at the industrial scale [15,16]. Thermal pretreatment results in the solubilization of organic compounds [9,19], disinfection by sterilization [20] and reduction of exogenous pollution [21], which favors the hydrolysis step, increases biogas production, and reduces the retention time [16,22]. Moreover, this process also enhances phase separation, which improves the recovery rate of floating oil. This oil can be used as the raw oil for biodiesel production [23], and its removal also effectively alleviates biological inhibitory reactions induced by the high concentrations of oil and grease in KW [12].

So far, most of previous studies have centered on analyses of the degradation efficiency of organic waste, such as KW and sludge and achieving higher degradation efficiency by various pretreatment methods, using mono-digestion and co-digestion [17,19,24–27] through AD tests, and no previous study has investigated the changes in the kinetic properties of the anaerobic digestion of KW after thermal pretreatment with various treatment temperatures and durations. Besides, the estimation of the economic feasibility of thermal pretreatment based on a full-scale application has only been reported for sewage sludge from waste water treatment plant and the cost estimation of conventional biological pretreatment has not been reported to date, which is still based on lab-scale level data [18]. We have evaluated the influence of thermal pretreatment on the physical and chemical properties of KW and determined the relationship between thermal hydrolysis and anaerobic biodegradability using batch test in [28,29], considering the variation of input substrate could result in a transient change in the composition of the microbial community in the AD system [24]. Thus, in order to achieve a comprehensive and deep understanding on the growing interest of thermal pretreatment method to enhance AD of KW, particularly the aim of demonstrating the relevant role played on the performance of the AD process by thermal pretreatment, the objective of this study was to investigate and evaluate the influence of thermal pretreatment which could cause changes in the input substrate KW on the hydrolysis rates of KW by applying the method proposed by Koch and Drewes [30] and the methane yields and lag phase by the modified Gompertz model [31]. Moreover, various modification characteristics and possible modification mechanisms are discussed, thus gaining insight into organics removal during KW anaerobic digestion and providing comprehensive and comparative conclusions to the new field of AD knowledge. Finally, the feasibility of the combined thermal pretreatment and AD system is expounded both economically and technically. Thus, reference could be provided for the selection and optimization of an economical and environmental friendly thermal pretreatment technique of KW.

2. Materials and methods

2.1. KW

The characteristics of KW are closely related to local living standards and eating habits, etc. In particular, according to investigations conducted in certain cities in China, food waste and bones account for more than 90% of KW, and the remaining proportions are mainly paper and plastic. The KW used in this study was collected from a canteen in Tsinghua University that can serve approximately 10,000 students and staff members per meal after manual sorting in order to remove impurities, such as big bones, plastics and metals. Specifically, the sorted KW consisted of cooked and uncooked food, and the major components were rice, pasta, fruit, vegetables and meat. KW was collected at the same time every day from the university canteen and stored at 4 °C in a refrigerator. After a continuous collection for a week, the KW was mixed with a kitchen blender to ensure uniform and representative experimental materials. It was then crushed into particles with an average size of 1–2 mm and also stored at 4 °C in a refrigerator. The basic compositions and characteristics of the KW used in this experiment are listed in Table 1a.

2.2. Reactors and processing method

A 20-L stainless steel thermal hydrolysis reactor constructed as a pressure vessel with a heating shell was used for the pretreatment of KW, and an automatic methane potential test system (AMPTS II) supplied by Bioprocess Control was used to study the effects of thermal pretreatment on the digestion of KW. The experimental system is shown in Fig. 1.

2.2.1. Thermal hydrolysis

Approximately 1 kg of KW was transferred into the vessel and preheated to a predetermined temperature for different treatment durations (Table 1b).

2.2.2. Centrifugation and three-phase separation

After hydrolysis at a certain temperature for a selected time, the KW samples were cooled to room temperature by circulating water

Table 1a
Compositions and characteristics of the KW.

Compositions of KW		Characteristics of the KW	
Parameters	KW	Parameters	KW
Cooked bone	2.6	pH	4.5 ± 0.2
Cooked eggshell	1.3	Total solids (%)	19.1 ± 1.1
Pasta & rice	27.7	Volatile solids (%, dry basis)	93.2 ± 1.4
Fruit peeling	20.9	Carbohydrate (%, wet basis)	11.8 ± 0.4
Cooked vegetable	24.3	Proteins (%, wet basis)	2.5 ± 0.2
		Lipids (%, wet basis)	3.5 ± 0.1
		Carbon (%, dry basis)	46.1 ± 1.6
		Hydrogen (%, dry basis)	7.0 ± 0.2
		Oxygen (%, dry basis)	37.8 ± 1.6
		Nitrogen (%, dry basis)	3.2 ± 0.4