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Enhanced nitrogen distribution and biomethanation of kitchen waste by thermal pre-treatment

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ABSTRACT

The effects of thermal pretreatment (90, 120, 140 and 160 °C) on the morphology (organic and inorganic nitrogen) and distribution properties (in solid phase, liquid phase and gas phase) of nitrogen in kitchen waste (KW) and on anaerobic digestion performance were investigated. The results show that thermal pretreatment could efficiently enhance the solubilisation of organic nitrogen compounds in KW, especially at high temperatures and long heating durations. Approximately 3.0–47.9% of organic nitrogen in KW decreases in total nitrogen content was obtained in the solid phase after thermal pretreatment. Higher biogas production and biodegradability of organics (in terms of the removal rate of soluble chemical oxygen demand, total organic nitrogen, and volatile solids) during subsequent anaerobic digestion were observed compared with the levels for untreated KW. An overall economic analysis indicates that the most profitable pretreatment process was achieved at 90 and 120 °C for treatment time of 30 and 15 min respectively, with a net potential profit (2–8 € ton^{-1} kW).

1. Introduction

A large amount of kitchen waste (KW) is produced yearly due to the increase in population and urbanisation. In China, more than 80% of KW is reutilised as animal feed, particularly for pigs, whereas a very small amount mixed into municipal solid waste is disposed of during the incineration or landfill process. All of these disposal techniques are facing challenges associated with both environmental and food safety considerations because of the high moisture content and concerns regarding foot and mouth disease [29,32].

KW is a good candidate for anaerobic digestion with the concomitant benefit of biogas production and recently most research has focused on the anaerobic digestion (AD) of KW due to the waste's high organic content and methane production potential [2,19,22]; additionally, anaerobic digestion with the addition of co-substrates, i.e., co-digestion with substrates to adjust and compensate alkalinity, such as sewage sludge [42], cattle and chicken manure [22,23] and kitchen wastewater [34], has been considered to be an effective and commercially flexible approach to reducing process limitations and improving methane yields [4].

Nitrogen mainly exists in two forms in KW including organic nitrogen (for example protein) and inorganic nitrogen (such as ammonia nitrogen) in both the solid phase and liquid phase. The features of nitrogen distribution in KW could provide information on the knowledge about the nutrients and design suitability of anaerobic digestion before entering KW into formal operation equipment. The protein content in KW is normally high in China, ranging from 11% to 28% (measured on a dry weight basis), which can cause inhibitory levels of ammonia and sulphide [9,11]. Such factors lead to low organic loading rates and biogas yields that prevent process failure and thus limit the application of anaerobic digestion in the recycling of KW if no sufficient buffering capacity is present [14,43]. Furthermore, the high protein content of KW can gives high nitrogen content on hydrolysis and lead to inhibitory effects from toxic ammonia or sulphide concentrations [5,9], thus leading to lower biogas yield and even process failure.

Moreover, numerous pretreatment methods (including mechanical, chemical, oxidative, thermal and biological disintegration) have been suggested to intensify the liquefaction and release of macromolecular organic particulates, thus improving digestion

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performance [3,13,21,25]. Among these pretreatment methods, thermal pretreatment under appropriate temperature and duration could enhance the solubilisation and anaerobic biodegradability of KW [21,25,26]. Besides, it could also enhance the separation properties of oil from water in KW and promoting the recycling of floating oil, which could be used as raw materials for biodiesel [36,38]. So, theoretically, thermal pretreatment can bring good economic benefits. The proteins in KW (with a proportion range of 11–28%, dry basis) could also provide a nitrogen source for microorganisms beyond inhibition during anaerobic digestion. In addition, the hydrolysis of particulate organic materials has been considered the rate-limiting step in anaerobic digestion, some authors have emphasized that the hydrolytic process still remains the least-well-defined step [17,28,31].

Hence, it is particularly important to investigate the effects of thermal pretreatment on the solubilisation and hydrolysis of proteins in KW as well as the effects on subsequent anaerobic digestion. Previous studies have mainly concentrated on the direct anaerobic digestion of KW and the combined digestion of other biomass waste, such as sludge, and have focused on adjusting parameters such as the pH, mixing ratios, retention times and organic loading [24,40,42]. Few studies have addressed the effects of thermal pretreatment on the distribution of nitrogen, waste oil recovery efficiency and the anaerobic digestion of KW.

The aim of this study was to study the influence of thermal pretreatment on the solubilisation effects of nitrogen compounds in KW in terms of forms and distribution of nitrogen and to evaluate the anaerobic digestion performance in terms of biomethanation potential and the biodegradability of organics. In addition, an economic analysis of the combined thermal pretreatment and anaerobic digestion of KW was performed.

2. Materials and methods

2.1. KW characteristics

KW was collected on a weekly basis from a university canteen. The major components were carbohydrates derived from bread, cooked noodles, rice and various vegetables and fruits; proteins and fat from different types of meat and fish. The KW was mixed using a kitchen blender to ensure uniform and representative experimental materials. The waste was then crushed into particles with an average size of 1–2 mm and stored at 4 °C in a refrigerator. Table 1 shows the basic characteristics of the KW.

2.2. Thermal pretreatment

Thermal pretreatment was performed in a 20-L stainless steel hydrolysis reactor, which was designed to withstand pressures as high as 2.0 MPa and temperatures as high as 220 °C. Approximately 1 kg kW was transferred into the vessel and preheated to a predetermined temperature (90, 120, 140 and 160 °C) for different treatment durations (15, 30, 50, 70, 90 and 120 min).

After treatment at a certain temperature for a selected period, samples were cooled to room temperature by circulating 10 °C water. Some of the KW samples were centrifuged at 5000 r/min for 5 min, which separated the KW into three distinct layers: from top to bottom, oil, liquid and solid phase. All three phases were removed for subsequent experiments and analyses. The sponge with excellent hydrophobic and oleophilic properties was used to remove oil phase from KW.

Table 1
Characteristics of the KW.

Sample	pH[a]	TS[a,c]	C[b]	H[b]	N[b]	S[b]	O[b]	VS[a,c]	CP[a,c]	CC[a,c]
KW	6.5	18.7%	46.1%	6.9%	3.2%	0.3%	37.8%	17.5%	2.8%	10.4%
SD[c]	0.2	0.4	1.7	0.2	0.3	1.6	0.0	0.4	0.2	1.9

[a] Measured on wet-weight basis of kitchen waste.
[b] Measured on dry-w eight basis of kitchen waste.
[c] TS: total solids; VS: volatile solids; CP: crude protein; CC: crude carbohydrate; SD: standard deviation.

2.3. Anaerobic digestion tests

After centrifugation, the liquid phase and solid phase of KW was blended thoroughly and added in the anaerobic digestion reactors. Batch anaerobic digestion tests were carried out in 3-L glass bottles at 35 °C to measure the biogas productivity of the raw and thermally treated materials. The seed sludge was obtained from a steady operational digester in one waste water treatment plant with 2-day gravity sedimentation prior to inoculation. 250 g kW (the feed (F)) and 2500 g seed sludge (inoculums (I)) were put into the reactors with the F/I ratio of 0.73 on a volatile solids (VS) basis. Then the upper space of each reactor was flushed with nitrogen for at least 3 min to assure the anaerobic conditions and then sealed quickly. In each experimental run, three control digesters were operated. At the same time, two blank digesters which contained inoculums only were incubated at the same time to correct for the biogas yield from the inoculums. The digestion experiments were run for approximately 30 days.

Specific methane production can be modelled using the commonly cited first-order decay predictor equation [41]:

$$Y = Y_m \times (1 - \exp(-kt)) \tag{1}$$

where Y is the cumulative specific methane yield for a given time t, Ym the ultimate specific methane yield and k is the first order decay constant.

2.4. Economic analysis

Economic analysis of the combined thermal pretreatment and anaerobic digestion of KW included calculation of the cost required by the thermal pretreatment of KW, and benefits achieved from the additional biogas production obtained by the thermally pretreated KW compared to the production obtained from the raw KW. Two possible scenarios in the energy market for the biogas produced during anaerobic digestion include selling the biogas as thermal energy or selling it as green electricity [26,37].

After thermal pretreatment and sequenced centrifugation, the removed oil that floats on the surface, referred to as crude oil, can be recycled and utilised for biodiesel production [27,35]. The selling price of crude oil in the Chinese market ranges from 350 to 530 €/t. Considering the expenses of long-distance transport and pretreatment fees during transesterification, the net profit of crude oil is calculated to be 142 €/t, based on an inquiry and investigation of a normal, operating biodiesel plant in China.

The extra cost ($EUR_{\text{extra cost}}$) cause by thermal pre-treatment was calculated by an electricity meter which was connected with thermal hydrolysis reactor used to measure the electricity consumption for the whole thermal pretreatment process.

The extra benefits can be calculated as:

$$EUR_{\text{extra-benefit}} = E_{\text{biogas}} \cdot V_{\text{biogas}} \cdot f \cdot EUR_{\text{kWh-price}} + m_{\text{floating oil}} \cdot EUR_{\text{floating oil-price}} \tag{2}$$

where E_{biogas} is the energy content of biogas with 65% CH_4 (6.5 $\text{kWh}_{\text{total}}\ \text{m}^{-3}$) [37], V_{biogas} is the extra biogas production due to thermal pre-treatment (m^3), f is the energy conversion yield factor