Aerobic composting of digested residue eluted from dry methane fermentation to develop a zero-emission process

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ABSTRACT

Digested residue remained at the end of a process for the production of fuel ethanol and methane from kitchen garbage. To develop a zero-emission process, the compostability of the digested residue was assessed to obtain an added-value fertilizer. Composting of the digested residue by adding matured compost and a bulking agent was performed using a lab-scale composting reactor. The composting process showed that volatile total solid (VTS) degradation mainly occurred during the first 13 days, and the highest VTS degradation efficiency was about 27% at the end. The raw material was not suitable as a fertilizer due to its high NH_4^+ and volatile fatty acids (VFAs) concentration. However, the composting process produced remarkable results; the physicochemical properties indicated that highly matured compost was obtained within 62 days of the composting process, and the final N concentration, NO_3^- concentration, and the germination index (GI) at the end of the composting process was 16.4 g kg^{-1}-TS, 9.7 g kg^{-1}-TS, and 151%, respectively. Real-time quantitative PCR (qPCR) analysis of ammonia oxidizers indicated that the occurrence of nitrification during the composting of digested residue was attributed to the activity of ammonia-oxidizing bacteria (AOB).

1. Introduction

A large amount of organic waste is produced from kitchen and from the food industry worldwide, and its disposal has become a major environmental problem. Development of efficient utilization systems for these wastes is essential to create a recycling-based society (Morita and Sasaki, 2012). Because these wastes are rich in starches, they can be converted to valuable products such as ethanol. Ethanol is an attractive renewable fuel that can serve as a motor fuel substitute for gasoline (Balat et al., 2008; Balat, 2011).

A previous study has shown that kitchen garbage can be successfully utilized for the production of fuel ethanol (Tang et al., 2008). Moreover, a two-stage fermentation process was developed to utilize kitchen garbage for the production of fuel ethanol and methane (Koike et al., 2009) as shown in Fig. S1 (Supplementary materials). Approximately 85% of the energy from the garbage was converted to fuel ethanol and methane using this process. However, digested residue was still eluted after the dry methane fermentation. In order to develop a zero-emission process, this digested residue could be composted to produce a soil conditioner or fertilizer. Although composting has been widely applied in the

treatment of different kinds of organic wastes, including agricultural, municipal, and food waste, as well as livestock manure (Bernal et al., 2009; Chen et al., 2014; Maulini-Duran et al., 2014; Sundberg et al., 2013; Zhang et al., 2011), knowledge gaps still exist in understanding the composting process for digested residue and the resulting compost quality (Bustamante et al., 2013; Franke-Whittle et al., 2014; Tambone et al., 2015; Zeng et al., 2016).

A high maturity index is essential for the successful application of compost as a soil conditioner and fertilizer. Nitrification activity is indicative of compost maturity because it is thought to occur at the maturation stage, when temperatures are mild (Sánchez-Monedero et al., 2001) and volatile total solid (VTS) degradation has stopped or declined to a very low level (Zeng et al., 2012). Moreover, nitrification can naturally neutralize the compost through the release of H⁺ (Caceres et al., 2006; Nolan et al., 2011), making it beneficial as a fertilizer.

Nitrification consists of two stages: ammonia-oxidizing bacteria (AOB) and/or archaea (AOA) oxidize NH_4^+ to NO_2^-, which is then oxidized to NO_3^- by NO_2^--oxidizing bacteria (NOB). NH_4^+ oxidation is the rate-limiting step in nitrification (Yao et al., 2011). It was believed that the AOB and/or AOA oxidize ammonia to nitrite during composting, depending on the composting materials. Zeng et al. (2011) compared the relative contribution of AOA and AOB

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to nitrification during agricultural waste composting process, and found that AOA were abundant throughout the composting process, including the thermophilic and cooling stages, whereas AOB were also associated with ammonia activity especially during the mesophilic and maturation stages. There is one report having previously been addressed on evolution of ammonia oxidizers during composting of digested residue (Zeng et al., 2014). Their report indicated that AOB instead of AOA were responsible for nitrification during aerobic composting of digested residue. In addition, nitrogen dynamic and microbiological evolution during aerobic treatment of digested residue were very different from that of fresh wastes, and the composting process of digested residue was suggested to be prolonged to consume the excessive NH_4^+/NH_3. However, the quality of the end-product was not evaluated.

Therefore, the possibility of composting the digested residue eluted from dry methane fermentation was studied to obtain an added-value fertilizer in a zero-emission process. Composting of digested residue by adding matured compost and a bulking agent was performed using a lab-scale composting reactor. The physico-chemical properties of the raw material and the composting samples during the composting of digested residue were investigated, and the maturity of the end-product was evaluated. Moreover, the evolution of ammonia oxidizers, i.e., AOB and AOA, during the composting process was monitored by real-time quantitative PCR (qPCR).

2. Materials and methods

2.1. Composting materials

Fig. S1 (Supplementary materials) shows a block diagram for the production of ethanol-methane from kitchen waste using a two-stage fermentation process. The digested residue used in this study was obtained from a thermophilic dry methane fermentation process. Briefly, kitchen garbage collected from the canteen of Sichuan University, China, was first used for ethanol production, and the residue after ethanol distillation (distilled residue) was subjected to thermophilic dry methane fermentation (52 °C) at a VTS loading rate of $1 \, g \, kg^{-1}$-sludge·d^{-1}. While preparing the digested sludge compost, matured compost and sawdust were added as accessory materials. The weight ratio of the digested residue, matured compost, and sawdust in the mixture was 3.5:1:1. The physico-chemical properties of the raw materials are shown in Table 1. The digested residue had a high moisture content of 80.6% and a low C/N ratio of 13.2. Sawdust with a high C/N ratio and low moisture content was added as a bulking agent. Matured compost was also added to introduce various aerobic microorganisms to the mixture as is typical for composting (Franke-Whittle et al., 2014). The matured compost was produced from a solid fraction of dairy manure, using a lab-scale composter (Fig. 1) in our lab (Sun et al., 2016). The moisture content of the mixture was 61.9%

and was slightly higher than the optimal range (50–60% moisture content) for composting (Gajalakshmi and Abbasi, 2008).

2.2. Composting set up

Fig. 1 outlines the lab-scale composting reactor system. A cylindrical glass reactor (300 mm diameter × 400 mm high) was fitted with a flat removable lid. Since a lab-scale composting process is more vulnerable to external effects (e.g. heat loss), the temperature in composting pile was monitored and controlled by a microcomputer. An electric ribbon heater surrounding the reactor was used to control the temperature. As shown in Fig. S2 (Supplementary materials), the temperature was increased from room temperature at a constant rate (e.g., 0.5 °C h^{-1}). When the temperature in composting pile reached a set point of 60 °C, it was maintained for 3 days set in advance with heating switched on or off. The heater was then turned off until the temperature in the composting pile dropped to the other set point of 35 °C and this temperature was maintained until the end of the composting process. The reactor was embedded in a nylon cloth and a polystyrene foam to minimize heat loss. The reactor had three holes in the lid; two for the insertion of thermocouples and one was the outlet for the exhaust gas. Two thermocouples were used to measure the temperature of the center and the top of the compost pile. The exhaust gas from the middle hole was passed through two conical flasks containing a 2% w/v H_2SO_4 solution to absorb the NH_3, cooled and dried, and then injected into an infrared analyzer (RI-550A, Riken Co., Ltd, Tokyo) to determine the CO_2 content of the gas. At the bottom of the reactor, a perforated polyvinylchloride (PVC) plate (bearing 500 3-mm holes in a 300-mm diameter plate) was installed to support the compost and to distribute the air uniformly. An air stream from a compressor was supplied to the reactor continuously at a constant rate, from below the PVC plate after passing through a flowmeter (PFM710-C6-C-M, SMC, Tokyo). The thermocouples and flowmeters were connected to a computer for auto-recording the data throughout the experiment. The previous study showed good performance reproducibility using the composting reactor system (Sun et al., 2016).

The composting process for the raw material with an approximate volume of 22 L (5.5 kg) was carried out in the aforementioned reactor and the aeration rate was maintained at $0.2 \, L \, kg^{-1}$-TS·min^{-1} during the entire composting process. Prior to the composting run, the digested residue, matured compost and sawdust were mixed thoroughly by hand to ensure maximum homogeneity. In addition, the composting mass was moved from the reactor to a separate container in the room, and mixed manually on day 0, 5, 9, 13, 21, 28, 40, 55 and the end of the composting process. Samples (about 30 g) were taken at the beginning, and after each turning, and then at the end of the composting process. The samples were divided into two parts, which were stored at 4 and −20 °C, respectively. The temperature of the composting pile, the inlet

Table 1
Physicochemical properties of the raw materials used in the composting experiment.

	Moisture content (%)	VTS (%TS)	pH (−)	EC ($\mu S \, cm^{-1}$)	NO_3^- (g kg^{-1}-TS)	NH_4^+ (g kg^{-1}-TS)	TC (g kg^{-1}-TS)	TN (g kg^{-1}-TS)	C/N (−)
Digested sludge	80.6	57.3	8.0	4023.0	ND	11.8	360.5	27.1	13.2
Mature compost	52.5	75.7	7.4	2190.0	3.6	ND	290.3	25.1	11.6
Sawdust	10.9	97.3	8.4	NM	NM	NM	428.0	1.0	428.0
Mixture[*]	61.9	81.2	8.3	2004.0	0.8	4.1	367.9	15.0	24.5

VTS, volatile total solid; EC, electronic conductivity; TC, total carbon; TN, total nitrogen; C/N = TC/TN; ND, not detected; NM, not measured.

[*] Mixture (5.5 kg wet mass) was used as raw materials for composting experiment, and the weight ratio of digested residue, matured compost and sawdust in mixture was 3.5:1:1 based on wet basis. Theoretical CO_2 emission (L) from the raw material was calculated as follow (Eq. (1)):

$$\text{Theoretical } CO_2 \text{ emission (L)} = \frac{5.5 \times (1 - 0.619) \times 0.368 \times 22.4}{12} \times 1000 = 1439.5$$