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Production of nitrate-rich compost from the solid fraction of dairy manure by a lab-scale composting system

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ABSTRACT

In the present study, we developed an efficient composting process for the solid fraction of dairy manure (SFDM) using lab-scale systems. We first evaluated the factors affecting the SFDM composting process using different thermophilic phase durations (TPD, 6 or 3 days) and aeration rates (AR, 0.4 or 0.2 l min^{-1} -kg^{-1}-total solid (TS)). Results indicated that a similar volatile total solid (VTS) degradation efficiency (approximately 60%) was achieved with a TPD of 6 or 3 days and an AR of 0.4 l min^{-1} kg^{-1}-TS (hereafter called higher AR), and a TPD of 3 days resulted in less N loss caused by ammonia stripping. N loss was least when AR was decreased to 0.2 l min^{-1} kg^{-1}-TS (hereafter called lower AR) during the SFDM composting process. However, moisture content (MC) in the composting pile increased at the lower AR because of water production by VTS degradation and less water volatilization. Reduced oxygen availability caused by excess water led to lower VTS degradation efficiency and inhibition of nitrification. Adding sawdust to adjust the C/N ratio and decrease the MC improved nitrification during the composing processes; however, the addition of increasing amounts of sawdust decreased NO_3^- concentration in matured compost. When an improved composting reactor with a condensate removal and collection system was used for the SFDM composting process, the MC of the composting pile was significantly reduced, and nitrification was detected 10–14 days earlier. This was attributed to the activity of ammonia-oxidizing bacteria (AOB). Highly matured compost could be generated within 40–50 days. The VTS degradation efficiency reached 62.0% and the final N content, NO_3^- concentration, and germination index (GI) at the end of the composting process were 3.3%, 15.5 × 10^3 mg kg^{-1}-TS, and 112.1%, respectively.

1. Introduction

The number of dairy cows in China has exceeded 100 million because of the development of intensive feeding (Qian et al., 2014). This has resulted in a dramatic increase in the generation of manure. Large amounts of manure represent a pollution source with a high content of organic materials (Zhou et al., 2015). Manure has caused serious environmental problems, such as ground water pollution, odor problems, production of pathogens, and excessive occupation of land. Cattle manure is also potentially hazardous to human and animal health (Tian et al., 2012). It is therefore necessary to devise effective treatments to manage manure waste. Composting is a useful technology to stabilize organic waste, as well as produce organic fertilizer that can be used as a soil conditioner. Composing has been widely applied in the treatment of different kinds of organic wastes, such as agricultural, municipal, and food waste, as well as livestock manure (Bernal et al., 2009; Maulini-Duran et al., 2014; Sundberg et al., 2013; Zhang et al., 2011).

The composting process for livestock manure is usually conducted by adding a large amount of bulking material, such as straw or sawdust. Normally, co-composting livestock manure with bulking agents is an acceptable solution (Li et al., 2008), largely because of the higher MC and lower C/N ratio of livestock manure compared with the lower MC and higher C/N ratio of the bulking materials. However, this method increases the volume to be treated because of the low density of the bulking materials; consequently, the cost of composting increases. Transportation costs can also be a factor because of bulking materials, and is especially an issue when the bulking material and animal waste are not available at the same time. Furthermore, the active phase of the composting process is long because bulking materials decompose at a slower rate (Caceres et al., 2015). Consequently, several months or more are required to reach a mature end product. The production of high-quality compost in a short time period is necessary because of the volume of manure and shortage of land on which to store it in China. Negative effects of the addition of bulking materials on

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the quality of the end product were also reported by Magrí and Teira-Esmatges (2015), in which composting of cattle manure with bulking materials (hammer-milled municipal tree pruning waste) at a volumetric ratio of 1:1 limited the attainment of temperature of 55 °C due to the lower capability of heat retention. Thus, the use of bulking materials should be kept to a minimum when composting cattle manure to save processing costs and space within the treatment facility.

In recent years, solid-liquid separation of animal slurry, with the solid fraction used for composting, has garnered interest in intensive livestock production (Brito et al., 2012; Chowdhury et al., 2014). Although solid-liquid separation of animal slurry does not reduce mass, the solid fraction generated can be used for composting directly without adding bulking materials due to its reduced moisture (e.g., ⩽72%). This is a particularly important process for manure slurry management on intensive livestock farms, where land availability for slurry application may be limited. Brito et al. (2012) studied the feasibility of composting the solid fraction of cattle slurry without the addition of bulking materials. Their results indicated that agronomically effective organic soil amendment was produced using cattle slurry solid fraction over 168 days. However, significant nitrification occurred after day 100, and long-term composting was conducted because of the lack of intervention management (e.g., no aeration or no turning). Chowdhury et al. (2014) investigated the process dynamics in terms of important physical parameters (MC, bulk density, particle density, and air-filled porosity) and their physical relationships during composting of the SFDM. However, the quality of the end product was not evaluated.

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, at which temperatures are mild (Sánchez-Monedero et al., 2001) and degradation of volatile total solid (VTS) has stopped or declined to a very low level (Zeng et al., 2012). Moreover, nitrification can cause the natural acidification of the compost because of the release of H^+ (Caceres et al., 2006; Nolan et al., 2011); this acidification makes the compost beneficial as a fertilizer. In terms of quality, high nitrate (NO_3^-) concentration of compost is normally desired, because NO_3^-−N is a better form of N for many plants than NH_4^+ as the sole form of N (Gross et al., 2012). Lettuce plants exhibited faster growth with NO_3^--based fertilizer compared to NH_4^+-based fertilizer (Gross et al., 2012). Nitrification consists of two stages: ammonia-oxidizing bacteria (AOB) and/or archaea (AOA) oxidize NH_4^+ to NO_2^-, which is oxidized to NO_3^- by NO_2^--oxidizing bacteria (NOB). NH_4^+ oxidation is the rate-limiting step of nitrification (Yao et al., 2011). Thus, monitoring the activity of AOB and/or AOA would be beneficial in the prediction of compost maturity.

Composting research at the lab-scale is important for the development of optimized full-scale facilities (Baptista et al., 2012). Previous studies have evaluated the performance and reproducibility of composting (Lashermes et al., 2012), substrate compostability (Hu et al., 2009), and the influence of process parameters on the composting process (Petric et al., 2009) using lab-scale reactors (⩽10 l). However, limited studies have evaluated the quality of the end product such as nitrification and maturity, using lab-scale reactors. Indeed, it is difficult to conduct the composting process at the lab-scale successfully because of the limitations of downscaled experimental trails. The composting process is more vulnerable to external effects, such as heat loss at smaller scales (Chowdhury et al., 2014). To the best of our knowledge, information on the composting of SFDM to produce high-maturity compost in a lab-scale reactor system is quite limited.

The objective of our study was to produce high-maturity compost (i.e., nitrate-rich) from SFDM using a lab-scale composting system. First, effects of the thermophilic phase duration (TPD), aeration rate (AR), and C/N ratio on performance of the composting process were studied. Then, an improved lab-scale composting system was designed to help to guarantee the success of the composting process. Moreover, the relationship of nitrification and MC was examined, and monitoring of AOB and AOA during the composting process by real-time quantitative PCR (RT-*q*PCR) was investigated.

2. Materials and methods

2.1. Composting materials

The dairy manure slurry was collected from a dairy farm located in Shuangliu Country, Chengdu. The slurry was pressed using an oil press to separate the liquid from the solid. The resulting SFDM was used for the composting process. Table 1 shows the physicochemical properties of SFDM and sawdust. The MC of the separated SFDM was about 72%, which was similar to that separated by a commercial screw press separator (Brito et al., 2012). The C/N ratio of the SFDM was 18.2. Sawdust was obtained from a sawmill in Shuangliu Country, Chengdu. It had a lower MC of 11.9% and higher C/N ratio of 343.2.

2.2. Outline of lab-scale composing reactor systems

Fig. 1 outlines two types of lab-scale composting reactor systems. For system A, a 28-l cylindrical glass reactor (300 mm diameter × 400 mm high) was fitted with a flat removable lid. An electric ribbon heater surrounding the reactor was used to control the temperature, using personal computer. As shown in Fig. S1 (supplementary materials), the temperature was raised from room temperature at a constant rate (e.g., 0.5 °C h^{-1}). When the temperature in composting pile reached to a set point (e.g., 60 °C), it was maintained for days set in advance (e.g., 6 days) by heating on or off. Then, the heater kept off until the temperature in composting pile drop to the other set point (e.g., 35 °C) and the temperature was maintained till the end of the composting process (e.g., 66 days). The reactor was embedded in a nylon cloth and polystyrene foam to minimize heat loss. The reactor had three holes in the lid; two for the insertion of thermocouples and one for the outlet port for exhaust gas. Two thermocouples were used to measure the temperature of the center and 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 NH_3, was cooled and dried, and was then injected into an infrared analyzer (RI-550A, Riken Co., Ltd, Tokyo) to monitor 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 uniformly distribute the

Table 1
Physicochemical properties of SFDM and sawdust.

Materials	Content	
	SFDM	Sawdust
MC (%)	72.0 ± 0.7	11.9 ± 0.3
VTS (%TS)	81.6 ± 1.6	97.0 ± 1.1
pH (-)	8.43 ± 0.1	5.51 ± 0.2
NH_4^+ (mg kg^{-1}-TS)	1.04×10^3 ± 21.2	NM
NO_3^- (mg kg^{-1}-TS)	ND	NM
TC (%TS)	35.0 ± 0.5	42.2 ± 0.7
TN (%TS)	1.9 ± 0.1	0.10 ± 0.0
C/N (-)	18.2 ± 0.1	0.34×10^3 ± 1.8

SFDM, solid fraction of dairy manure; MC, moisture content.
VTS, volatile total solid; TS, total solid; TC, total carbon; TN, total nitrogen.
C/N = TC/TN; ND, not detected; NM, not measured.