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Research Paper

A lab-scale study on the influence of the compost-dewatering process on moisture removal and pathogen inactivation in pre-sanitized fecal sludge

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ABSTRACT

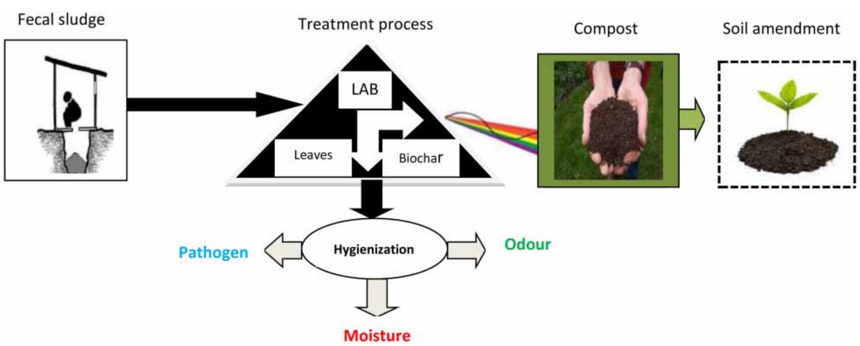
In many developing cities, fecal sludge management has become a serious environmental issue. As the increasing urban settlement results in the generation of fecal matter that causes environmental problems, recovering and recycling fecal waste for soil amendment could be beneficial. In this study, pre-sanitized fecal sludge (FS) was collected from the ongoing FS treatment process at the University of Science and Technology Beijing and subjected to a compost-dewatering process to mitigate pathogen and moisture content (MC). Biochar and dry leaves were added to reactors 1, 2, and 3 (1:1, 2:1, and 3:1) at 10% to facilitate the degradation process. The result shows that the final MC from the 45-day experiment has values of 35.1, 37.3, 38.9, and 65% in reactors 1, 2, 3, and the control, respectively. The indicator organism (fecal coliform) was completely mitigated in reactors 1 and 2. However, fecal coliform was merely reduced from 7.2 to 5.7 log10 CFU/100 mL in reactor 3 and remained available in the control reactor. This phenomenon of pathogen inactivation and MC removal from FS was attributed to the concentration of lactic acid bacteria (LAB) in the pre-sanitized FS. The addition of LAB to the treatment process enhanced the acidification process and resulted in pathogen inactivation. Biochar and dry leaves also played an important role in mitigating moisture and enhancing the fast composting process. Given the hygienic condition of the compost, it is suitable for soil amendment in agriculture.

Key words: biochar, compost-dewatering, fecal sludge, moisture content, soil amendment

HIGHLIGHTS

- Composting process enhanced pathogen and odor removal from pre-sanitized fecal sludge (FS).
- Acidification of FS as a pre-treatment method serves as a reliable method for fecal hygienization.
- Short-term composting process proved effective in odor emission mitigation.
- Method employed in this research enhanced fecal coliform inactivation.
- Compost derived from the process has a high potential to be used as an agricultural resource.

GRAPHICAL ABSTRACT



INTRODUCTION

Fecal sludge management (FSM) is a serious environmental issue that needs awareness and will play a key role in the management of future sanitation issues (Saxena *et al.* 2019). Onsite treatment technologies are usually viewed as temporary solutions until a permanent adequate system can be constructed (Penn *et al.* 2018). Nevertheless, the establishment of adequate septic tanks cannot be compared with the pace of urban augmentation, especially in low-income cities. In addition, the identification of fecal sludge (FS) as a very important component suitable for soil amendment has provided the route to the establishment of a resource recovery approach in sanitation.

The use of a sustainable sanitation process to produce rich organic fertilizers for agricultural use is one of the mechanisms for topsoil quality and improvement. Resource-oriented sanitation approaches provide solutions to environmental degradation, water scarcity, and recycled nutrients for agricultural products. Such sanitation systems could provide efficient resources, sustainable sanitation, and an economically sound alternative that protects both humans and the environment (Magri *et al.* 2015; Liu *et al.* 2018). FS has been used for many years in agriculture to increase soil fertility. However, it contains a high amount of pathogens that constitutes a threat to public and environmental health. Producing compost from pretreated human excreta could be effective in replenishing the soil and promoting plant growth while maintaining a hygienic environment (Yacob *et al.* 2018). The process could also promote sustainable soil fertility, which is a crucial challenge all over the world.

Fecal matter compost provides an important partway where the dewatering process assures a considerable reduction in pathogen content and storage volume (Fan *et al.* 2019; Zhang *et al.* 2019). However, compost-dewatering of pre-sanitized FS that was initially treated with the lactic acid fermentation (LAF) process has never been investigated. Compost-dewatering of pre-sanitized FS in this study is considered a low-cost and easy technology to facilitate waste management and sanitation in developing countries. This research attempts to close the gap in sanitation by providing a new research approach in FS treatment by recovering compost from pre-sanitized FS through the compost-dewatering process. Onsite inactivation of pathogen and odor removal is a very important measure for FS treatment aiming at the soil amendment. The process could also foster sustainable soil fertility, which is one of the major challenges in different parts of the world.

MATERIALS AND METHOD

Feedstock characteristic

Pre-sanitized FS was collected from the lactic acid fermented FS in the laboratory for further treatment. The fermented FS was a representative of the sludge under treatment for pathogen and odor elimination. The initial characteristics of the fermented FS are presented in Table 1. Due to the high moisture content (MC) of the pre-sanitized FS, the samples were sun-dried for 2 days to achieve the desired MC of within 75% for the compost-dewatering process. The vascular plant leaves that were used as an additive were collected from the University of Science and Technology Beijing campus. The leaves were sun-dried, chopped, and used as an additive during the compost-dewatering process, while the bamboo-derived biochar with an adsorption capacity of 70.92 mg/g was used to reduce the MC. A total of 10% of biochar and dry leaves were added to every treatment reactor except the control.

Procedures for compost-dewatering

Four laboratory-scale compost reactors made of plastic with a total working volume of 5 kg were used. The dimensions of the reactors were: a diameter of 34 cm, a height of 30 cm, and a thickness of 10 mm. The reactors were protected with wadding to prevent heat losses and then filled with fermented FS, dry leaves, and biochar up to 80% of the reactor's size. A thermometer

Table 1 | Initial characteristics of the fermented fecal sludge before the compost-dewatering process

Parameters	Control	Reactor 1 (1:1)	Reactor 2 (2:1)	Reactor 3 (3:1)
pH	7.9	3.8	4.6	4.2
Moisture content (%)	78.1	81	81.8	81.1
Fecal coliform (CFU)	8.1	0	0	7.3
Temperature (°C)	28	26	28	29
Lactic acid bacteria (CFU)	–	7	7.1	6.9

was fixed in the reactors to monitor the temperature changes. After loading the feedstock, the bioreactor top was covered. The oxygenating process was carried out through the opening located at the top of the reactor. Compost mixture was done manually using a metallic object placed beside the reactors to obtain constant mixing and provide oxygen as suggested by An *et al.* (2012). The method of aerating the compost materials through turning and mixing was adopted according to the procedure explained by Sorvari & Wahlström (2014) and Jindo *et al.* (2016).

The pre-sanitized FS was subjected to a compost-dewatering process for the removal of moisture. The MC of the sample from the control reactor was 78.8%, while the MC from reactors 1, 2, and 3 (1:1, 2:1, and 3:1) was 81, 80.8, and 81.1%, respectively. Reactors 1:1, 2:1, and 3:1 represent the ratio of the mixture of FS and lactic acid bacteria (LAB) concentration during the pre-sanitization process as reported in our previous study (Odey *et al.* 2018). However, the use of such high MC for the compost-dewatering process can create waterlogged or anaerobic conditions (Brinton 2000). Therefore, 10% of biochar was added to the three reactors, respectively. Likewise, blended dried leaves were added on a ratio of 1:0.2 w/w as recommended by An *et al.* (2012). The reason for adding dry leaves was to provide aerobic conditions to the degrading microbes and avoid anaerobic conditions during composting. All the experimental trials were replicated three times to confirm the results and apply the statistical analysis.

Odor evaluation

The odor variation during the composting process was evaluated by six people as reported in our previous study (Odey *et al.* 2018). The potency of the perceived odor was evaluated by using a scale ranging from 0 (no odor) to 6 (very strong odor).

Analytical method

The pH was determined directly with a microprocessor pH meter attached to pH electrodes InLab Routine. The pH value in every reactor was measured every 2 days. The fecal coliform count was determined using the membrane method with coliform agar, followed by incubation at 48 °C for 24 h. A colony-forming unit (CFU/100 mL) was used to calculate the number of bacteria available in each of the reactors using Chromocult Coliform agar. Temperature is a critical parameter to monitor the performance and rate of biological processes during composting (Wei *et al.* 2014). According to He *et al.* (2013), the breakdown of the composite substrate into easy components is aided by temperature. The temperature was recorded daily over the entire experimental duration. The MC and other parameters were measured according to the standard method. The amount of water is determined by subtracting the dry weight from the initial weight, and the MC is then calculated as the amount of water divided by the dry weight or total weight.

RESULTS AND DISCUSSION

Compost-dewatering process

The term compost-dewatering process in this research is referred to as the transformation of organic waste through biological means in the presence of oxygen (González *et al.* 2019; Kucbel *et al.* 2019; Yang *et al.* 2019). The dewatering of organic wastes allows the recovery of dewatered materials for use as a soil amendment. Mineralization and humification are important to convert organic materials into humus. The dewatering process in this study generated heat which created an environment that was important for the elimination of pathogens and odor removal. The quality of the final dewatered sludge depends on the various components such as temperature, pH, MC, and other important operational parameters such as turning frequency and oxygenation (Bian *et al.* 2019; Milinković *et al.* 2019).

Temperature change during the compost-dewatering process

The compost-dewatering temperature went through two phases such as mesophilic and cooling phases. During the entire period, the temperature ranged from 24 to 65 °C. The temperature of the bioreactors with biochar supplementation increased swiftly in comparison to the control reactor. Statistical analysis indicated that the concentration of biochar and their combined interaction had a notable impact on the temperature. The results show that the 10% biochar concentration had a substantial effect on temperature. It was noticed that trials with 10% biochar and dry leaves entered the mesophilic stage on the fifth day of the experimentation. The temperature was continuously increased and reached the peak values of 65 °C in trial 1:1 reactor, 63 °C in trial 2:1, and 68 °C in 3:1 reactor after 18 days of the experiment, while the temperature of the surrounding remained below 23 °C throughout the composting process. The Thermophilic stage lasted for over 30 days, and then increasingly entered a cooling stage. The process enhanced the pathogen and odor elimination. The increase in temperature in the reactors supplemented with biochar was probably due to the faster-dewatering process (Zhang & Sun 2014). The thermophilic temperature condition achieved in this experiment, coupled with the addition of biochar and dry leaves, provided a suitable condition for MC and pathogen mitigation.

Impact of compost-dewatering on MC

Optimum MC lies between 35 and 65% (Bernal *et al.* 2009; Moral *et al.* 2009). Figure 1 shows changes in MC in this experiment. The initial MC was 81, 80.8, 81.1, and 78.1% in reactors 1, 2, and 3 (1:1, 2:1, and 3:1) and the control reactor, respectively. The result showed that MC decreased in the three reactors amended with 20% biochar, except the control reactor. The lowest MC of 35.1, 37.3, 38.9, and 65% were observed in reactors 1:1, 2:1, and 3:1 and the control reactor after 35 days. The reduction was due to the porous structure of biochar that enables it to absorb moisture. Other reasons for this reduction could be related to the higher microbial activities that decompose the substrate with the release of water vapors. This phenomenon can further be explained that the porosity of biochar enhances aerobic conditions for the degrading microbes and the porous nature constitutes suitable habitat for microbial proliferation. Also, the high surface area of biochar enhances microbial activities that result in the rise in temperature and the degrading microbes (Yu *et al.* 2019). At 35 °C temperature, no significant changes in MC were observed.

Biochar porosity enables water absorption and creates a suitable avenue for the degradation process. Given the lack of addition of biochar to the control reactor, the MC of 65% was recovered on the final day of the treatment. High MC in the control reactor resulted in low-temperature rise, which led to the inhibition of oxygen supply to aerobic microbes for their normal metabolic activities.

Impact of compost-dewatering on organic matter degradation

Various biochemical reactions transformed complex substrates into simpler components that lead to the reduction of organic matter (OM) percentage (Safaei Khorram *et al.* 2016; Wu *et al.* 2019). Greater decomposition rates show higher microbial activities. Low degradation corresponded to the lower pH values at the beginning stage in comparison to the period when biochar and dry leaves were added. Considerably, when biochar and dry leaves were added to reactors 1:1, 2:1, and 3:1, high intensity of OM degradation was noticed. Maximum organic decomposition was noted in reactors 1:1, 2:1, and 3:1. The analysis revealed low changes in the control reactor, probably due to no supplementation of biochar and dry leaves.

After 45 days, the least significant changes were noticed in OM degradation, which may be due to all readily biotransformed microbes that fully degraded the materials. The OM percentage in the final compost was 58% in reactor 1, 56% in reactor 2, 51% in reactor 3, and 67% in the control reactor. Correspondingly, the lower degradation in control showed a high MC and a high percentage of unavailable OM.

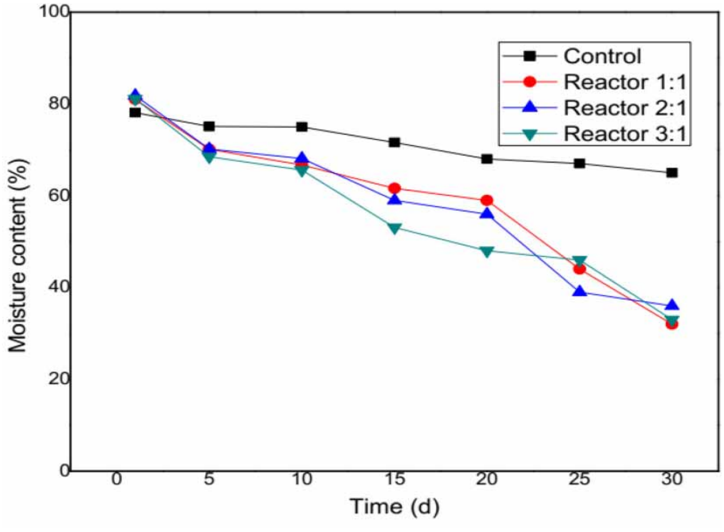


Figure 1 | Moisture content during the compost-dewatering process.

Fecal coliform composition during the compost-dewatering process

Figure 2 shows fecal coliform differences during LAF and the compost-dewatering process. It was observed that the indicator organism (fecal coliform) remained eliminated in reactors 1 and 2 (i.e. reactors 1:1 and 2:1). However, fecal coliform only reduced from 7.2 to 5.7 log10 CFU/100 mL and remained visible in the indicator reactor. This phenomenon can be attributed to the concentration of LAB in the treatment reactors and the mix ratio of fermented rice flour with fecal coliform as reported in our previous study (Odey *et al.* 2018). The high concentration of LABs in the FS in reactor 1 led to the elimination of the indicator organism within 20 days of the LAF and 30 days in reactor 2. A Similar trend was also observed in reactor 3. The inactivation of fecal coliform in this study presents a new research layout for the production of cheap materials to eliminate pathogens and odors in FS and make it suitable for application in soil amendment.

On the final day of the compost-dewatering process, the indicator organism was only visible in the control reactor and few were found in reactor 3:1. It is recommended that high temperature is important when treating FS because it allows the removal of the available pathogen (Hagemann *et al.* 2018; He *et al.* 2018).

Compost yield

Compost derived from the FS process has a high potential to be used as an agricultural resource. In addition to the option for cost reduction in fecal waste management, closing the loop on sanitation by recovering nutrients from FS can substitute mineral fertilizers in rural and urban agriculture and hence reduce pollution (An *et al.* 2012). The biological test results show that no fecal coliform bacteria were found in reactors 1 and 2. In addition, no other bacteria were found in the two reactors, except in the control and reactor 3. Conversely, the compost produced in reactors 1 and 2 demonstrated adequate qualities. Table 2 shows the characteristics of the compost at the final treatment. Given the hygienic quality of the compost recovered from reactors 1 and 2, it can directly be applied in agriculture for soil amendment. A long-term field experiment on acid and alkaline soils indicated that, by increasing compost doses, soil organic matter content was increased in acidic soil by 2–6.9% (Buczko *et al.* 2018). Through the effect of compost on soil organic matter and thus soil physical properties, compost can help to prevent the degradation of land resources. The degradation of land is characterized by the loss of soil production strength.

Odor offensiveness of the compost

The qualitative responses from six observers to the questions concerning the presence of fecal odor and the acceptability of the perceived odor for agriculture use indicated that the treatment process suppressed the odor from the compost and replaced it with a lactic acid smell. Apart from the evaluation from the six observers, the variation of the odor was obvious to the researcher during the laboratory experiments and analyses. In another study, LAF of swine manure added with LAB

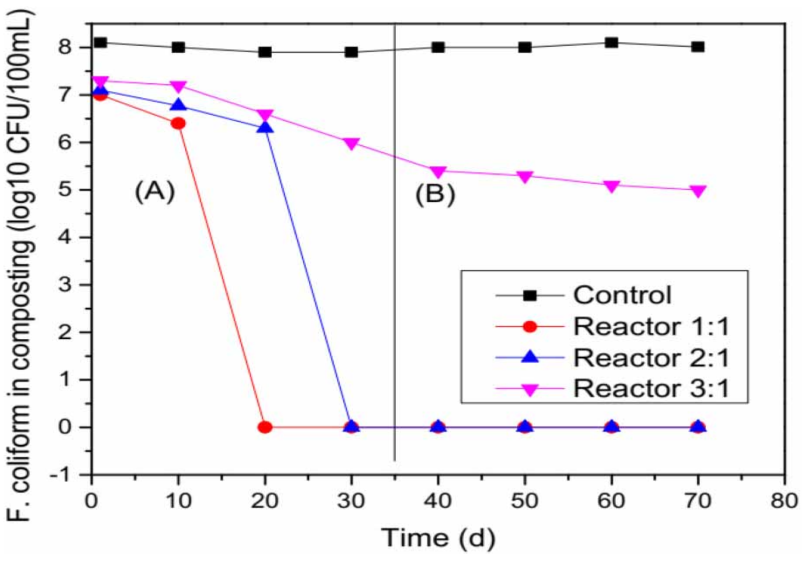


Figure 2 | Fecal coliform differences during the LAF and the compost-dewatering process. (a) Fecal coliform variation during the fermentation process in the previous study. (b) Fecal coliform variation during the composting process in the current study.

Table 2 | Characteristics of sludge after the compost-dewatering process

Parameters	Control	Reactor 1:1	Reactor 2:1	Reactor 3:1
pH	8.9	6.7	6.9	7.2
Moisture content (%)	65	37	39	40
Fecal coliform (log10 CFU/100 mL)	8.1	0	0	5.3
Temperature (°C)	25	31	24	22
Lactic acid bacteria (log10 CFU/100 mL)	–	6.9	6.2	6.4

reduced the odor (Huang *et al.* 2006). The odor reduction in the current study could make the compost suitable for agriculture as a soil amendment.

Limitation of the study

The current study was limited to the University of Science and Technology Beijing and the rural Beijing community, with an emphasis on the sanitization of FS for soil amendment through the composting process. The study did not include other parts of the country. The inclusion of other regions would possibly have fortified the study and permitted greater insights into the subject of discussion.

CONCLUSION

The new FS management system (compost-dewatering) was proposed. The study investigated the efficiency of the compost-dewatering process on water and pathogen removal from pre-sanitized FS. The addition of 10% biochar and dry leaves contributed to the rapid decrease in MC in the three reactors except for the control reactor. The final MC of 35.1, 37.3, 38.9, and 65% were observed in reactors 1, 2, 3, and control. The 45 days of the composting process ensure hygienic compost. The system can be implemented with a net advantage, considering the value of recovering hygienic compost materials from the process within a short period. The process could enable the provision of economically self-sustained sanitation system services that could boost local agricultural production, through the utilization of safely treated final sanitation products. The optimization of the process proved that the system could effectively inactivate pathogens in FS within a short period. It is recommended that further research should focus on the implementation of the various sanitation approaches discussed in this study for the production of sanitized compost for soil amendment.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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