Effect of matured compost and exogenous microbial inoculants on the composting process of digestate eluted from dry anaerobic digestion

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Abstract. Biogas and digestate can be produced by anaerobic digestion of pig manure and straw. However, further treatment of digestate should be carried out. The digestion efficiency is affected by the addition of extra biodegradable materials or inoculants. This study was conducted to reach a less emission and higher efficient of the composting process. The windrow composting of the digestate by adding mature compost and exogenous commercial microbial inoculants was performed by two assays per variation. The composting process showed that the digestate treated with exogenous microbial inoculants reached a 10-20% higher organic matter loss than the digestate without exogenous microbial inoculants. The plant-nutrients (N, P, K) were significantly increased due to the positive effect of exogenous microbial inoculants, especially the HK microbial inoculants. Adding matured compost can reduce the plant-nutrients loss caused by leaching from digestate, which is with high moisture content. Meanwhile, the concentrations of toxicant heavy metals in digestate were also increased after composting due to organic compounds decomposition and concentration effect. Additionally, the heavy metals concentrations in compost are still under the standard. In general, the results illustrated that windrow composting can be added to enhance the composting efficiency and resource recovery of pig manure and straw.

1. Introduction
Since the demands of waste treatment and resource recovery are rising, anaerobic digestion is in popularity as an efficient approach to produce biogas from organic waste. During the treatment process, most of the nutrient elements in the feed stock remain in the digestate while a small portion will be converted into biogas. In China, the rising biogas industry brings increasing requirement of high-value application of digestate [1].

Simultaneously, the digestate could present high concentrations of potential phytotoxic compounds including ammonium, intermediate organic acids and pathogens [2]. Previous evidence shows that the heavy metal content in digestate is quite high. For example, the content of Cu and Zn in the dry digestate of pig manure are 1016 mg/kg and 2628 mg/kg, respectively [3]. Through plant cultivation
experiments, it was found that digestate application can significantly increase the contents of heavy metals accumulated in plants, indicating that the application of digestate without treatment might bring environmental pollution and cause health risk to human beings [4,5]. In addition, the high moisture content of the digestate make its storage and transportation inconvenience. These features make the direct application of digestate limited. Consequently, it is recommended to treat the digestate by aerobic composting to reduce potentially toxic compounds and convert it into value-added fertilizer or soil conditioner before land application.

Organic matter composting is an efficient approach for nutrients recycling, organic stabilizing and eliminating pathogen [6]. Besides, it can transform organic matter (OM) into soil matured conditioners [7]. Different composting system [8], process parameters [9], input materials and its formulation [10], and the environmental condition are all influencing factors for the quality of the compost. The problems of high moisture content of digestate can be solved by mixing dry materials with low water content [11]. The matured compost is always added to the mixture due to its developed aerobic biomass and low moisture content. Additionally, some commercial microbial inoculants used for composting can be bought from the market, that mainly contains lactic acid bacteria, photosynthetic bacteria and yeasts. The addition of exogenous microbial inoculants was reported to increase enzymatic activities [12], accelerate the breakdown of OM [13] and promote the composting efficiency [14,15]. However, some authors suggested that only if under certain environment conditions, the microorganisms could enhance organic degradation successfully [16]. For example, it was reported that the microorganisms showed no significant effect on the food waste degradation of small scale [17]. Although there have been relevant works on the effects of solely adding dry materials or microbial inoculants on digestate composting, how the simultaneous addition of dry materials and microbial inoculants affects the changes of nutrients and pollutants during digestate composting remains unknown. Clearly, this effect warrants investigation given its expected importance to promoting the digestate-compost quality and safe use in soil.

Therefore, a comprehensive study was conducted to study the composting of digestate eluted from dry anaerobic digestion of pig manure and straw, both of which are important contributors to rural organic solid waste. The effects of the recycling matured compost and the commercial microbial inoculants on the composting efficiency were analyzed. Meanwhile, the nutrients in the compost were evaluated. Dry aerobic composting not only converts digestate into fertilizer with high value and achieve resource recovery, but also prevents secondary pollution by direct digestate application.

2. Materials and methods

2.1. Composting materials

In this study, the digestate was leached from dry anaerobic digestion of pig manure and maize straw. The thermophilic dry anaerobic digestion was operated at 52 °C with total solid content of about 20%. Mechanical treatments were carried on the wastes to remove impurities, and then screen through 20 mm sieve. The mixture of organic matters were sent to anaerobic digester for dry digestion. A screw press separator was used to separate the digestate from solid fractions. 15 kg solid fractions were collected after the separation. Subsequent chemical analysis and composting process were conducted on the solid fraction. According to the characterization, the digestate was with high moisture but relative low OM content. More detailed properties of the digestate were shown in Table 1.

| Table 1. Characteristics of the materials for the composting experiment. |
|-----------------|-------|------|-----|-----|-----|-----|-----|
|                 | Moisture (%) | pH   | OM(%) | N(%) | P(%) | K(%) | C/N |
| Pig manure      | 77-83        | 8.015| 54.7 | 1.67 | 3.15 | 0.87 | 19  |
| Maize straw     | 13-18        | 7.165| 96.3 | 0.97 | 0.33 | 1.75 | 57.59|
| Digestate       | 68-71        | 8.345| 77.5 | 1.64 | 3.07 | 1.38 | 27.41|
| Back matured compost | 40-45  | 7.573| 68.02| 2.37 | 5.04 | 0.75 | 16.65|
2.2. Composting experimental design
The windrow composting experiments were carried out for 30 days at the ambient temperature (15–20 °C). The effect of addition of recycling mature comports on the biodegradation of digestate during composting procedure was investigated. Two types of commercial microbial inoculants were purchased from Beijing WoTu Tiandi biological Technologies Inc (VT) and Key Laboratory of National Environmental Protection and Groundwater Pollution Simulation and Control, China Research Academy of Environmental Sciences (HK). These two microbial strains are bacillus and yeast, respectively, and the number of effective viable bacteria reached 10^9 CFU/mL.

The experimental treatments were shown as follows: Fresh digestate (FCK); Fresh digestate+VT microbial inoculants (FVT); Fresh digestate+ HK microbial inoculants (FHK); Fresh digestate (70%)+ Back matured compost (30%) (BCK); Fresh digestate (70%)+ Back matured compost (30%)+VT microbial inoculants (BVT); Fresh digestate (70%)+ Back matured compost (30%)+ HK microbial inoculants (BHK).

2.3. Composts chemical and biological analysis
A digital thermometer was used during the composting process. The following parameters was analyzed for each sample: pH, moisture content and OM. pH was measured in a slurry of 1:5 solid/water (v:v). The moisture content was measured based on the amount of water lost at 105 °C. The concentration of OM was analyzed with an elemental analyzer (VARIO EL cube) after treatment with dilute HCl (0.5 M). The N, P and K contents were tested by the Spectroquant test kits and expressed by the total nitrogen content (N), soluble potassium (K_2O) and soluble phosphate (P_2O_5) respectively. Contents of Cd, Pb, Cr, Cu and Zn were determined using ICPMS (Varian, Fort Collins, USA) after reverse aqua regia digestion. To insure its accuracy of the analyses, standard samples and blanks were used simultaneously during the analysis.

2.4. Mathematical analysis
Parallel tests were performed during the analysis and double repeated (n=2). The values were expressed with mean ± SD from the duplicated measurements. ANOVA was conducted using SPSS 20.0 (SPSS, Inc.) to compare effects between different treatments at P < 0.05 level.

3. Results and discussion
3.1. Effect of addition of matured compost and exogenous microbial inoculants on the physicochemical property of compost
The he fluctuation of composting temperature is in important index in each treatment. As is shown in Figure 1, the temperature of the composting trials had three stages including mesophilic stage, thermophilic stage and cooling stage. The fast growth of temperature at the initial days was caused by the microbial activity. the temperature on the initial days roaring to above 55 °C for BCK, BVT and BHK, and 60 °C for FCK, FVT and FHK, directly entering the thermophilic phase. The most active thermophilic reaction in composting systems was usually happened at temperature from 52 °C to 60 °C [18]. For disinfection, the composting temperature must be kept at 50–55 °C for 5 to 7 days or above 55 °C for 3 days, according to “Hygienic Requirements for Harmless Disposal of Night Soil (GB7959-2012)” of China. Potential pathogen can be killed at thermophilic temperature to achieve sterilization. It is showed that all the trial temperatures were above 55 °C for 8 days and then decreased to room temperature eventually. After the thermophilic stage, a rapid temperature decrease was noted, it is believed to be caused by the heat loss, which happened in common in labscale reactors [19,20]. Pile temperature kept steady and similar to the ambient environment.
Figure 1. Temperature variation during composting. (a), BCK; (b), BVT; (c), BHK; (d), FCK; (e), FVT; (f), FHK.

As in Figure 1, the variations of temperature during composting were similar between treatment with and without commercial microbial inoculants. At the thermophilic stage, the digestate treated with commercial microbial inoculants BVT and BHK reached a 8–12% warmer temperature than the digestate with no exogenous microbial inoculants. Both of the commercial microbial inoculants treated samples exhibited a potential capacity of raising the digestate temperature to thermophilic demand at the initial stage. This indicated that exogenous microbial inoculants can enhance the population and activity of the microorganism in the digestate.

Figure 2. pH variation during composting. (a), BCK; (b), BVT; (c), BHK; (d), FCK; (e), FVT; (f), FHK.
The pH of the compost affects the composting efficient in a significant way. In this study, the pH values were kept in the scope of 6–7.5 optimum for bacteria and 5.5–8.0 optimum for fungi [21]. The digestate is generally alkaline and the matured compost has lower pH (Table 1). Thus, the pH in the digestate with matured compost is lower than that without matured compost. The pH values were decreased by approximately 0.5 unit after composting in all trials (Figure 2). This result indicates that our composting system can alleviate the problem of digestate being alkaline. The pH decrease was caused by the breakdown of organic matters into low-molecular fatty acids and CO₂.

Moisture is considered as an important index of decomposition rate. Because of the increasing temperature and evaporation during the composting process, water content will be lower. In all the composting trials, moisture content decreased from 60–65% to 40–45% (Figure 3). Certain moisture values are required to meet the survive conditions of the organisms. Besides, leachate formation was not observed during the composting period.

OM provides main carbon and energy source for microorganism in composting, which indicates the degree of maturity and can be a criteria of the quality of the compost. According to former research, OM can be decomposed and transformed to stable humic compounds during the composting process. This reaction can buffer pH and provide nutrients for the plants [18,21]. The OM decreased most in FHK (30.5%). Higher OM loss in trials with HK was observed compared to the trials with VT and without microbial inoculants (Table 2). It was observed that OM can reduce most by about 25.7% in water hyacinth rotary drum composting in other research, while this research showed about 30% OM loss with microbial inoculants. Higher temperature was considered as a factor for more OM loss during thermophilic stage when treated with microbial inoculants. Therefore, the result suggested that OM degradation can be promoted by adding exogenous microbial inoculants and increasing pile temperature.

### 3.2. Effect of addition of matured compost and exogenous microbial inoculants on the plant-nutrients (N, P, K) in compost

The variation of plant-nutrients including N, P, K during the composting process is depicted in Table 2. The TN contents experienced decreasing stage, increasing stage and fluctuation stage subsequently.
The early decreasing stage might be caused by the intense NH$_3$ emission. After composting, the TN contents in BCK, BVT, BHK, FCK, FVT and FHK increased by 17.3%, 5.5%, 40.9%, 12.7%, 10.9% and 11.24%, respectively. Compared with the other treatments, the TN content increased the most in BHK and FHK, which was added with HK microbial inoculant, whereas the increase of TN content in BVT and FVT was less than the trial without microbial inoculant. The increase in TN might be due to the decrease of dry mass by the transformation of organic matter into CO$_2$. Besides, the nitrogen-fixing bacteria also plays a positive role in increasing N values the end of composting process [20).

Table 2. Plant-nutrients (OM, N, P, K) variation during composting.

| Plant-nutrients | Sample     | BCK     | BVT     | BHK     | FCK     | FVT     | FHK     |
|-----------------|------------|---------|---------|---------|---------|---------|---------|
| OM (%)          | digestate  | 89.2    | 89.3    | 92.3    | 89.2    | 87.8    | 86.7    |
|                 | intermediate | 85.2    | 79.6    | 83.6    | 82.9    | 79.6    | 83.6    |
|                 | decrease   | -4.5%   | -10.9%  | -9.4%   | -7.1%   | -9.3%   | -15.1%  |
|                 | compost    | 78.6    | 63.5    | 64.8    | 78.7    | 68.0    | 60.3    |
|                 | decrease   | -11.9%  | -28.9%  | -29.8%  | -11.7%  | -22.6%  | -30.5%  |
| N (%)           | digestate  | 1.91    | 2.00    | 1.86    | 1.97    | 2.02    | 1.82    |
|                 | intermediate | 1.63    | 1.82    | 1.61    | 1.74    | 1.87    | 1.45    |
|                 | variation  | -14.7%  | -13.3%  | -13.3%  | -11.7%  | -7.4%   | -20.3%  |
|                 | compost    | 2.24    | 2.11    | 2.62    | 2.22    | 2.24    | 2.27    |
|                 | variation  | 17.3%   | 5.5%    | 40.9%   | 12.7%   | 10.9%   | 24.7%   |
| P (%)           | digestate  | 4.34    | 4.13    | 4.11    | 3.97    | 4.96    | 3.12    |
|                 | intermediate | 4.23    | 4.88    | 4.44    | 3.76    | 3.79    | 3.19    |
|                 | variation  | -2.5%   | 18.2%   | 8.0%    | -5.3%   | -23.6%  | 14.2%   |
|                 | compost    | 4.75    | 4.48    | 5.45    | 4.61    | 5.34    | 5.21    |
|                 | variation  | 9.4%    | 8.5%    | 32.6%   | 16.1%   | 7.7%    | 40.1%   |
| K (%)           | digestate  | 0.66    | 0.63    | 0.69    | 0.79    | 0.79    | 0.66    |
|                 | intermediate | 0.71    | 0.72    | 0.72    | 0.73    | 0.74    | 0.64    |
|                 | variation  | 7.6%    | 14.3%   | 4.3%    | -7.6%   | -6.3%   | -3.0%   |
|                 | compost    | 0.67    | 0.69    | 0.76    | 0.85    | 0.87    | 0.74    |
|                 | variation  | 1.5%    | 9.5%    | 10.1%   | 7.6%    | 10.1%   | 12.1%   |

P and K are important nutrients for root growth and plant metabolism [22]. However, they are known to be easily leached out. At the composting initial stage, the P and K in the digestate without back matured compost decreased because of the leaching since the fresh digestate is with high water content, while the P and K increased with the addition of the matured compost. Therefore, the P and K can be maintained by decreasing of the moisture content. Subsequently, the P and K in the final composts increased in all trials due to a concentration effect. The same as the TN, the P and K content increased the most in BHK and FHK compared with the other treatments. These results indicated that there is a positive effect of microbial inoculants, especially the HK microbial inoculants, for supply nutrient to soil by enhancing the NPK of compost (>5%).

3.3. Effect of addition of matured compost and exogenous microbial inoculants on the heavy metals of compost

An important criterion of compost assessment in view of its environmental impact (mainly in agriculture) is determined by its heavy metal contents. The concentration of heavy metal in the
compost would be under the regulatory level. The following are the thresholds for heavy metals contamination in the unit of mg/kg: Cd-30, Pb-50, and Cr-150 (Chinese standard GB 18382-2012). However, some other toxic heavy metals are not regulated in the Chinese standard. In this experiment, five kinds of heavy metals, including Cd, Pb, Cr, Cu and Zn, were analyzed to investigate how composting affects the pollution risk of digestate compost application. It is reported that heavy metals exist in several states including soluble state, exchangeable state, binding state to carbonate, binding state to Fe-Mn oxide, binding state to organics, and remnant state [23]. Unlike the organic components of compost, heavy metals do not undergo biological breakdown, therefore compost products becomes enriched in metals in comparison with the fresh material. The contents of the heavy metals in the compost can be ranked as Zn > Cu > Cr > Pb > Cd.

Zn occurred in the organic waste mostly in fraction III associated with Fe/Mn oxides (up to 70% of total content) and in form of carbonates (up to 20% of total content). It should be pointed out that Zn is a metal showing high affinity to carbonates, therefore, it will be easily precipitated and coprecipitated with those compounds [24]. The results showed that the Zn content was significantly higher than other heavy metal elements in the digestate and remarkably increased by 38.5% and 46.7% in the compost with back matured compost and in the fresh digestate compost, respectively (Table 2). Cu is generally regarded as harmless metal and plays an important role in plants several biological processes, such as photosynthesis, carbohydrate allocation, respiration and seed production [25]. In this research, the concentration of Cu in the compost varied from 132.7 to 162.9 mg/kg (Table 3). The concentration of Cu in BCK and FCK were remarkably increased by 17.0% and 22.8% respectively at the end of the composting. However, at present, the Chinese national standard has not stipulated the threshold limit for Zn and Cu.

4. Conclusions
According to this study, the digestate leached from dry anaerobic digestion of pig manure and straw can be transformed into fertilizer after composting. The caparison was conducted between the composting processes with and without the application of two types of commercial microbial inoculants. Both two types of commercial microbial inoculants showed a slightly better OM degradation. Therefore, it is suggested that adding microbial inoculants could enlarge OM degradation, as well as increase the composting efficiency by increasing the temperature. The microbial inoculants,
especially the HK microbial inoculants, can rise the N, P and K contents (>5%) for providing nutrition to soil mainly due to a concentration effect. However, the toxicant heavy metals were also increased due to organic compounds decomposition and concentration effect. In general, all of the heavy metals values are within the threshold limits.

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