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# Co-composting of the Biogas Residues and Spent Mushroom Substrate: Physicochemical Properties and Maturity Assessment

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## Abstract

Recycling of BR and SMS are crucial for the development of biogas industry and commercial mushroom cultivation. The seed germination test is limited to examine the maturity of compost because of lacking the effect of insoluble part on plant growth. The aim of this study was to evaluate the maturity of compost by analysis the relationship between agronomic parameters of plant growth with physicochemical parameters of compost. The thermophilic period (over 50℃) was lasted 52 days. TOC, C/N, AP and $NH^{4+}$-N was decreased along with composting process, while TK, TP, AK and $NO_3^-$-N showed an opposite trend. As for seedling quality, the raw material (T0) showed the worst plant growth but the 100% compost (T1) showed better seedling quality compared with commercial seedlings. According to the analysis of Spearman correlation, the results indicated that TOC, C/N, $NH_4^+$-N, $NO_3^-$-N, AK and

lignocellulose can be used to evaluate compost maturity.

**Key words:** biogas residues, spent mushroom substrate, seedling quality, compost, maturity

## 1. Introduction

*Auricularia auricula* is a major edible fungus grown in northeastern China, with production of approximately 2.5 million tons in Heilongjiang Province alone. The high volume of waste associated with *A. auricula* production, consisting of more than 6 million tons of spent mushroom substrate (SMS) annually, is not currently disposed of efficiently due to the presence of sawdust in the substrate (Meng et al., 2018b).

During anaerobic fermentation, organic matter is decomposed by microorganisms under anaerobic conditions to produce biogas, which is rich in methane. This process reduces the environmental pollution associated with certain types of waste, produces biogas as an energy source, and reduces the demand on nonrenewable energy sources such as fossil fuels. China has a long history of biogas utilization. As of the end of 2015, China’s annual output of biogas was approximately 19 billion $m^3$, and “The National Rural Biogas Development Plan in 13th Five-Year” includes ambitious goals for the rapid development of the biogas industry. However, the process of anaerobic digestion is associated with the production of relatively large amounts of biogas residues (BR), which are difficult to handle and can easily cause secondary pollution. So the feasibility of BR is related to the development of biogas industry.

Composting is one of the most efficient technologies used to treat and dispose of organic wastes because it limits overall environmental pollution and produces compost that is suitable as a fertilizer and soil amendment (Wang et al., 2017). In addition, compost reduces the incidence of plant diseases by suppressing soil-borne pathogens, provides essential nutrients for plant growth, and improves soil properties (Bernal et al., 2009; Bustamante et al., 2008). Therefore, composting could be a suitable way of disposing of BR; however, because of their particular chemical and physical properties, especially the presence of lignocellulose, these waste products are not suitable for composting alone.

As for compost, the assessment of compost, and of biodegradable organic matter in general, quality has been the key issues especially in lignocellulose composting. In general, stability and safety are the two indexes for evaluating the maturity of the compost(Komilis, 2015). Stability means the extent to which the raw material has been decomposed by microorganism. While, safety refers to the effect of plant growth. The maturity of compost is often tested by measuring single-factor indexes, such as temperature, ammonia nitrogen, nitrate nitrogen, nitrification index (NI), cation exchange capacity, or germination index (GI)(Xiao et al., 2017). These indexes can reflect compost maturity to some extent, but the raw materials used for composting are complex, and thus single-factor indexes are not comprehensive indicators of compost maturity(Czekała et al., 2017; Komilis, 2015). For example, when the temperature of a reactor gradually drops to room temperature after a high temperature period, this change may be due to insufficient amounts of oxygen or water, which can inhibit the metabolism of microorganisms; if sufficient water or oxygen is added, the high temperature of the reactor will be restored(Guo et al., 2012). Researchers have developed methods using numerous indicators for comprehensive evaluation of maturity, including measurement of lignocellulose, as well as the presence of particular microorganisms corresponding to different stages of maturity (Castillo, 2013; Meng et al., 2018b). However, the precise impacts of compost on plants and soil organisms cannot be fully evaluated by the use of these physical and chemical indicators alone. For example, high electrical conductivity can be toxic for plants, but an appropriate amount of irrigation water will decrease the concentrations of salts in compost and thus reduce their effects on plants. Therefore, researchers developed the GI (Germination Index) as an indicator to evaluate the safety of compost, and the GI has been broadly accepted for evaluating compost quality (Luo et al., 2018). However, the GI is measured using leachate from compost, and thus the harmful effects of many insoluble substances in compost on plants cannot be explained using this method. When seeds absorb nutrients from endosperm transformed to compost, the effect of compost on plant root growth and nutrient uptake is important concerns. And the characteristics of compost itself can also affect the growth of plant roots and the development of aboveground parts. Because of the inadequacy of the germination method, the correlation between the germination index and other physical and chemical indexes can not convince compost maturity. Some researchers use other small plants or animals to evaluate the safety and maturity of compost, but these methods still cannot be used to evaluate the impact the maturity of the compost on plant growth (Young et al., 2016; Luo et al., 2018). Therefore, plant growth is the most direct and effective way to evaluate the compost maturity and the physicochemical indexes of maturity determined by plant growth have wider adaptability and credibility.

In this study, the effects of BR and SMS on composting time and the quality of the compost end-product were assessed. The physical and chemical properties of the compost were measured during the composting process, and the relationships among these parameters were evaluated in the context of compost maturity. Furthermore, seedling experiments were conducted to access the biosafety and nutritional value of compost. Finally, the relationships between seedling quality and compost properties were used to assess compost maturity.

## 2. Materials and Methods

### 2.1. Compost materials and preparations

The main composting materials were SMS, BR and pig manure (PM). SMS was obtained from an *A. auricula* workshop in Dongning County, Heilongjiang Province, China. BR was obtained from biogas plant feeding corn stock from Zhuozhou, Hebei Province, China. PM was obtained from a swine breeding herd in Zhuozhou, Hebei Province, China. SMS, BR and PM were mixed at a 1:1:1 ratio and composted from September to December in 2014.

### 2.2. Compost process

Composting was conducted at the organic fertilizer production workshop at the Zhuozhou Experimental Station at China Agricultural University. The concrete composting bunker was 40 meters long, 2 meters wide and 1.2 meters high, and the composting pile was 5 meters long, 2 meters wide and 1 meter high. When the compost temperature rose above 50 ℃, the compost was turned over manually. The turning frequency was once per day at the thermophilic stage and once per 5 days after the compost temperature fell below 35 ℃. Composting was allowed to continue for 118 d. Using a five-point sampling method, a sample of fresh compost (1 kg) was collected from three locations in the piles (surface, 25 cm depth; core, 60 cm depth; and bottom, 90 cm depth) at day 0, 5, 10, 15, 25, 35, 45, 65, and 105. A portion of each sample was stored at -20 ℃ for further chemical analysis and the seedling experiments.

### 2.3. Seedling assay

The compost from the process described above was mixed with peat on a volume basis. The compost was mixed with perlite and peat. A peat:perlite mixture (5:1, v:v) with (F-CK) and without (CK) fertilizer were used as the control treatment. The treatments were shown in Table 1.

The experiment had a randomized complete block design with four treatments and two replicates. A polystyrene tray with 72 cells was used as substrate container for plant growth (one seed per cell). The tomato was raised in the trays. Plants were grown in a controlled greenhouse environment from April 2016 to May 2016. They were randomly distributed within the experiment and rotated once per week until the end of the experiment. The plants were irrigated with distilled water equally for all treatments in accordance with their water demand during the growing period. No fertilization was used in any treatment except F-CK treatment. After 36 days of growth, at which point the plants had reached a size suitable for commercial transplantation, 20 seedlings were selected randomly from 20 cells per tray for analysis.

### 2.4. Analysis Methods

A thermometer was inserted at three locations in the compost piles (surface, 25 cm depth; core, 60 cm depth; and bottom, 90 cm depth) every day, and the average temperature was recorded. All composting parameters, including total organic carbon (TOC), total nitrogen (TN), total potassium (TK), total phosphorus (TP), pH, electrical conductivity (EC), lignocellulose, available potassium (AK), available phosphorusand (AP), nitrate and ammonium nitrogen ($NO_3^-$-N and $NH_4^+$-N) were determined according to methods reported by Meng (2018a and 2018b). Plant height was measured from the base region of the root to the top of the plant. Stem diameter was measured at the base of the cotyledon. The leaf area of the first (counting from the top) expanded leaves was measured using a CI-203 Handheld Laser Leaf Area Meter (CID Bio-Science, Inc., Camas, WA, USA). Spearman correlational analysis was performed using SPSS 20.0 (IBM Co., Armonk, NY, USA).

## 3. Results and Discussion

### 3.1. Temperature of compost

Temperature is one of the primary parameters used to monitor the composting process, because it changes in a manner related to the decomposition of organic matter and the growth of microorganisms. As shown in Fig. 1, the compost temperature rapidly rose above 40 ℃ when PM was added. The temperature increased rapidly during the first 6 days of the experiment, during which the ambient temperature was 21.5–27.5 °C, which was suitable for microbial growth. The PM contained a large amount of available nutrients and abundant microorganisms, which expedited the change in temperature (Tambone et al., 2015). During this period, supplemental microorganisms in the PM decomposed organic substances, which resulted in the accumulation of heat.

The temperature rose above 50 ℃ on the 6th day of the experiment and remained above this threshold for 52 days. At this stage, the pile was manually turned over every 2 days. The incorporation of SMS and BR, which are primarily lignocellulosic materials, lengthened the composting process and induced a persistent thermophilic period similar to that observed during composting of cow manure BR and SMS from *Auricularia auricula* production (Meng et al., 2018b; Zhao et al., 2013) A thermophilic phase of 3 days is sufficient to meet sanitation requirements meant to ensure the production of compost free of weed seeds and pathogens (Wang et al., 2017).

Over the following 29 days, the average temperature plummeted from 48.5 ℃ to 28 ℃, and the turning frequency was decreased to once every 5–10 days. At this stage, the metabolic rate decreased as the temperature fell, which indicated the onset of the maturation period(Bernal et al., 2009). During the maturation period, additional components in SMS and BR were decomposed, while nitrification was enhanced.

During the final 30 days, the temperature was reduced slowly from 25.4 ℃ to 12 ℃, and the compost was turned twice. A rapid decrease in temperature was observed after turning because of the heat loss caused by the low ambient temperature, as has been commonly reported for most composting processes (Zhang and Sun, 2014). At the beginning of the composting process, the raw material was light brown in color with a large particle size, lumped BR and an extremely unpleasant odor. After more than 100 days of composting, the compost lacked odor or insects, and it was dark brown in color, loose, and granular, which indicated that the final product was mature and sanitary.

### 3.2 Physicochemical parameters

#### 3.2.1 pH and EC

pH is an important factor in the composting process. Generally, a pH of 6.7–9.0 supports good microbial activity during composting. This factor is particularly relevant because of N losses by ammonia volatilization, which can be particularly high at pH >7.5 (Bernal et al., 2009). As shown in Fig. 2, the pH increased abruptly during the initial 5 days of the experiment, followed by a stable downward trend over the next 20 days, a precipitate from day 25 to day 35, and finally a slow decline until the end of the experiment. The increased pH was likely related to the increased denitrification, which indicated that the rate of $NH_3$ release was greater than the immobilization rate of nitrate nitrogen. Later, a sharp reduction in the release rate of

$NH_3$ reduced the Nitrification Index (NI) and pH (Zhang et al., 2016). At the end of the experiment, the pH was slightly decreased because of reduced microbial activity. The final compost product was very slightly alkaline (7.2) and thus suitable for seedlings (Bustamante et al., 2008).

EC is related to the mineralization of organic matter and the concentrations of mineral fractions, and it can indicate possible phytotoxic or phytotoxic-inhibitory effects. As shown in Fig. 2, EC showed a trend opposite that shown by pH. The initial decrease in EC may have been cause by ammonia volatilization and precipitation of mineral salts. EC was increased at day 10, likely because of the decomposition of organic matter and water loss by evaporation, which resulted in a net loss of dry mass (Silva et al., 2009; Bustamante et al., 2008). The final EC values were beyond the upper limit of 4.0 mS/cm and thus considered pernicious for edaphons.

### 3.2.2 Conversion of C and N

The TOC content increased gradually from 385.562 mg/g in the raw material to 399.505 mg/g on day 10, after which it steadily decreased (Table 2). These results are similar to those reported in a recent study (Meng et al., 2018b). In the present study, a relatively severe decrease in TOC was observed; however, SMS and BR were both rich in lignocellulose, resulting in relatively stable TOC content during the thermophilic and maturation stages. Similar results were reported in a study of straw and biochar compost (Zhang et al., 2016). TN content increased slightly during the initial 5 days of the experiment, although ammonia stripping was severe at this stage (Fig. 3), primarily because the rate of carbon loss was higher than the rate of N loss (Huang et al., 2017). TN content decreased slightly from day 6 to day 10 of the experiment. These results show that microbial metabolism was high during the thermophilic phase, while the rate of nitrogen consumption was significantly higher than the rate of dry matter degradation, as reported in other studies (Bernal et al., 1998). After the thermophilic phase, TN content gradually increased to 2.33% at day 65 because of organic matter decomposition, after which it decreased during the final 55 days of the experiment.

Carbon and nitrogen are used by microorganisms for energy production and cell growth during composting, which results in considerable changes in the C/N ratio, which can be used to assess the maturity of compost (Table 2).The initial C/N ratio of the raw material was near the optimum range (25-20) and thus presented the correct balance for the process to proceed efficiently. Except for the upward trend from day 5 to day 10, the overall trend of the C/N ratio was downward, primarily because the decomposition rate of carbon was lower than the rate of ammonia stripping. The decrease in the C/N ratio during the composting period was very similar to that reported in a previous study (Zhang et al., 2016) and probably caused by mineralization of the substrate or an increase in total nitrogen following carbon degradation (Zhang and Sun, 2014). At the end of the composting process, the C/N ratio was 13.5. A C/N ratio of 12 is normally accepted as indicative of a good degree of composting maturity (Fourti, 2013).

Fig. 3 shows the time course of $NH_4^+$-N content, $NO_3^-$-N content and the NI during the composting process. The amount of $NH_4^+$-N decreased from 1.99 mg/g to 0.02 mg/g during the composting process. However, this change in the $NH_4^+$-N concentration was not typical of those normally observed during the composting process. During composting, increased $NH_4^+$-N content is typically observed during the early stage of the process due to conversion of organic-N into $NH_4^+$-N by ammonification (Zhang et al., 2016). In the present study, the amount of $NH_4^+$-N may have decreased because organic-N had already been converted into $NH_4^+$-N by ammonification when the corn straw was subjected to methane fermentation. The $NO_3^-$-N concentration was relatively low and stable during the first 25 days of composting (Fig. 3). Generally, $NO_3^-$-N formation resulting from nitrification is limited during the first few days of the composting process because the activity and growth of ammonia oxidizers are likely to be inhibited by the higher temperature and lack of dissolved oxygen caused by intensive organic matter degradation (Gao et al., 2010; Zhang and Sun, 2014). Subsequently, the $NO_3^-$-N content gradually increased to 0.82 mg/g when the high $NH_4^+$-N concentration dropped, resulting in rapid growth of nitrifying bacteria and archaea. In term of quality, a high nitrate concentration is normally desired in compost, because $NO_3^-$-N is better for many plants as the sole source of N in comparison with $NH_4^+$-N (Gross et al., 2012) The NI ($NH_4^+$-N/$NO_3^-$-N ratio) has been used to evaluate compost maturity (Rashad et al., 2010). As was true for the pH level, the highest NI was obtained during the first 15 days of composting, and it dropped to 4.49 at day 25. Subsequently, a gradual decrease in the NI was observed during the maturation and cooling stages, and the NI of the end-product was approximately 0.01 (Fig. 3). A NI of less than 0.16 is indicative of compost maturity, so the end-product of the composting process performed for this study was mature(Rashad et al., 2010).

### 3.2.3 Nutrition of P and K

Phosphorus is the second limiting nutrient after nitrogen in most soils used for crop production. As shown in Table 2, TP content increased slightly during the composting process, while available P gradually decreased. The increase in TP content was mainly due to the loss of dry matter by organic matter decomposition. The loss of available P was probably due to mineralization of organic P and consumption by microorganisms, because P is important for cell growth and development (Sanchez et al., 2017;

Biederman and Harpole, 2013). TK content and available K increased during the thermophilic stage. Like nitrogen and phosphorus, potassium is one of the primary macronutrients required by plants for biological processes. Potassium is crucial for enzymes, coenzymes, protein synthesis, and photosynthesis. Approximately 90% of potassium in soil exists in insoluble forms in rocks and minerals like silicates. Water-soluble potassium is available to plants, but nonexchangeable potassium can also be taken up by plants when levels of exchangeable potassium are low (Sanchez et al., 2017). Therefore, the increase in available potassium content indicates that the compost was beneficial to the effective transformation of potassium, which favored plant growth.

### 3.2.4 Lignocellulose dynamics

The starting material was composed of 20.49% cellulose, 24.05% hemicellulose and 10.60% lignin, whereas the end-product was composed of 16.15% cellulose, 13.27% hemicellulose and 10.79% lignin (Fig. 4). Lignocellulose is extremely resistant to microbial degradation. Approximately 45% of the hemicellulose in the starting material was degraded during composting. In contrast, cellulose content steadily decreased during the composting period, with only 21% of cellulose decomposed by the end of the experiment. In comparison with most other lignocellulosic materials, SMS and BR are rich in cellulose and hemicellulose, but their decomposition rate in the present study was relatively low in comparison with those reported in other studies (Jurado et al., 2015; Paradelo et al., 2013). Lignocellulose is not degraded during the early stage of composting because more readily biodegradable compounds are present. Lignin acts as a protective factor for the cellulosic and hemicellulose fractions, and lignin biodegradation usually begins late and proceeds at a very slow rate (Jurado et al., 2015). When the supply of readily available nutrients is exhausted, lignocellulose contributes to the maintenance of the organic matter decomposition process and supports the microorganism population. Moreover, ammonia disrupts the structure of lignin, so the abundant ammonia in the raw material enhanced lignin degradation, which released hemicellulose and cellulose. In addition, during the thermophilic period, lignin degradation promotes the decomposition of hemicellulose and cellulose. However, during a composting period of 118 days, the decomposition of lignocellulose showed a similar rate to that recorded for SMS composting (Meng et al., 2018a; Zhang and Sun, 2014). Lignocellulosic wastes are composed of complex heteropolymers that are challenging for microorganisms to degrade due to inhibition of cellulosic enzymes (Manuel Castillo et al., 2013). Lignin levels remained unchanged throughout the composting period. Therefore, as previously hypothesized, the prolonged cooling stage observed during in composting may have been related to the presence of large amount of nutrients (Table 2) retained by the lignin fraction that were slowly released from the polymeric matrix.

### 3.3 Seedling quality

After composting, the end-product was used as a soil amendment for tomato seedlings. The seedlings were grown for 36 days to reach a size suitable for commercial transplantation, after which horticultural parameters were measured. The membership function method was used to evaluate the physiological indexes of tomato plants in different substrates (Zhang, S et al., 2015). The formula used for this analysis was as follows:

$X(f)=(X-Xmin)/(Xmax-Xmin)$

where $X$ was the measured value of a certain horticultural parameter under the substrate, $Xmax$ was the maximum value of the parameter, and $Xmin$ was the minimum value of the parameter.

The results of the evaluation of the seedling quality of tomato seedlings in different media are shown in Table 3. Tomato seedlings grown in T2 medium, in which 80% of the peat was replaced with compost, showed the best growth parameters. Some of the growth parameters of the tomato seedlings grown in T1 medium, including leaf number, height, stem diameter, and ground fresh weight, were nearly as high as those of the T2 seedlings. All of the seedlings grown in compost-based substrate (T1, T2, T3 and T4) showed better or comparable seedling quality in comparison with those grown in the CK and F-CK substrates. Although the 100% compost substrate produced the second-best seedling quality among the substrates, the 100% compost substrate showed obstructed seedling growth in comparison with the 80% compost substrate because of differences in physical and chemical parameters. Peat provided an appropriate pH (5.8–6.8) and EC (<2 mS/cm) for seedling growth, while 100% replacement of peat by compost increased the pH and EC to values that may have inhibited biological activity and plant growth (Zhang et al., 2012). Moreover, according to a previous study (Abad et al., 2001), the acceptable range of P for compost is 0.02–4.00 mg/g, whereas that of K is 0.10–5.00 mg/g. The P and K concentrations of the compost produced in this study exceeded these concentrations, so the T1 substrate slightly suppressed seedling growth in a situation similar to that reported by Meng (Meng et al., 2018a) Seedlings grown in substrates treated with N, P, and K have greater fresh and dry weights of the shoots and roots in comparison with those grown in substrates not amended with these elements. An amendment of 20% compost could provide nutrients appropriate for plant growth and thus meet the fertilizer requirements of commercially grown seedlings. The significant enhancement of crop growth and biomass production observed following the addition of chemical fertilizer corroborates the reports of many others (Eudoxie and Alexander, 2011).

Seedlings grown in substrate T0 showed the lowest seedling quality. In substrate T0, organic matter decomposition led to the accumulation of heat, which was toxic to the seedlings (Meng et al., 2018a). In addition, the amount of ammonia in the raw material may have also suppressed germination and plant growth (Meng et al., 2018a). During the composting process, organic matter in the raw material was mineralized to form a stable humus, and thus the final compost end-product was a suitable substrate for seedlings. In most countries, peat-based growth media that has no renewable nature and excessive exploitation will cause environmental problems is the main substrate in most commercial factory seedling. And the cost of growing media can reach 23% of the total cost, so low cost and renewable substrate was needed to replace peat in seedling production. The price of peat for vegetable or horticulture could reach at 4000 ¥/t, while the price of organic fertilizer was about 800-1000 ¥/t. The 100% compost (T1) showed better seedling quality than commercial peat-based substrate. So, compost replace peat as vegetable or horticulture seedling substrate could get more than 3 times of profit.

The similarity among treatments was evaluated based on the parameters of the seedlings using a hierarchical cluster analysis (Fig. 5). Using a cut-off of 10 for the normalized linkage distance, three clusters were identified. (i) The first cluster was formed by the T1, T3, T4, and F-CK substrates. Therefore, the quality of the seedlings grown in substrate T1 was to that of seedlings grown in substrates T3, T4 and F-CK. Therefore, the substrate with 20% compost instead of peat provided an appropriate fertilizer for commercial seedlings without further chemical amendment. In addition, the mature compost can be used as seedling media in organic agriculture (Olaria et al., 2016). (ii) The second cluster was formed by the CK and T0 substrates. The physical and chemical properties of the seedlings grown in each substrate were significantly different, but seedlings grown in the CK and T0 substrates showed the worst quality among the treatment groups. The germination of seedlings in the CK substrate was comparable with those in the F-CK and compost-based substrates, but the relative lack of nutrients in the CK substrate slowed plant growth. Seedlings grown in the T0 substrate showed a low quality, mainly because of unmaturity substrate that was unsuitable for root growth and contained phytotoxic component. (iii) The third cluster was formed by the T2 seedlings, which presented the best seedling quality. Therefore the addition of 80% compost produced a substrate with sufficient nutrients for plant growth and optimal physicochemical properties, which resulted in the best seedling quality among seedlings grown in the tested substrates.

### 3.4 Assessment of maturity

Although plant growth is the most reliable way to evaluate compost maturity, plant growth takes a lot of time. Therefore, it is very important to find fast and easily measurable physical and chemical indicators to evaluate compost maturity. A correlation matrix (Table 4) showed some significant relationships between the physical and chemical compost parameters. There were strong positive linear relationships between composting time and both TP and AK (r=0.94, r=0.952, P=0.01, respectively), which indicated that phosphorus was mineralized and potassium was converted to an available form during the composting process. There was also a strong positive linear relationship between composting time and both $NO_3^-$-N and TK (r=0.879, r=0.873, P=0.05, respectively). The composting time and the TOC, $NH_4^+$-N, AP and C/N ratio showed strong negative correlations (r=-0.923, r=-0.991, r=-0.952, r=-0.926, P=0.01, respectively). The composting time is directly related to the maturation of the compost, so TOC, the C/N ratio, $NH_4^+$-N, $NO_3^-$-N, TP, TK, AP, and AK could be used to determine compost maturity. Next, a principal component analysis (PCA) was performed to identify factors that could be used to distinguish the relationships between physicochemical parameters (Fig. 6). The parameters were grouped according to principal components in four clearly distinguished clusters. Group I included pH; group II included TOC, the C/N ratio, AP and $NH_4^+$-N; group III included AK, TN, TK and TP; group Ⅳ included composting day, EC and $NO_3^-$-N. TK and TP both showed a positive correlation with AK; moreover, TK, TP and AK were clustered in the same group, so AK was regarded as the most representative indicator among the three parameters. Thus, as shown in Table 4 and Fig. 6, TOC, the C/N ratio, $NH_4^+$-N, $NO_3^-$-N, AP, and AK could be used to determine compost maturity.

When compost is added to soil, it directly affects numerous factors, including pH, EC, TOC, TN and the supply of mineral nutrient elements, which affect the growth of plants. Therefore, compost must be mature and stable to be safely applied in agricultural applications (Qian et al., 2014). The seed germination test is commonly used to examine the toxicity of compost because it is sensitive to environmental pollution (Luo et al., 2018). In this study, the GI of raw material before composting was nearly 82% and remained above 80% during the whole composting process, which could be considered as safe substrate for plant growth. However, the seedling quality in T0 was unqualified compared with CK (Table 3). As known, in the seed germination test, only the leachate liquor from compost is used to verify the suitability of the physicochemical characteristics of the compost for plant growth. While in BR and SMS, the water soluble component was digested in reactor and decomposed in mushroom growth respectively. But, the effects of pathogens, porosity, nutrition, and component conversion on plant growth are not assessed by the seed germination test. Therefore, after 36 days of seeding, the relationships between compost physicochemical parameters and seedling quality were determined (Table 5). There was a strong negative linear relationship between seedling quality and both the C/N ratio and AK (r=-0.885, r=-0.857, P=0.05, respectively). In addition, a strong negative linear relationship between seedling quality and lignin was observed (r=-0.948, P=0.01). Moreover, cellulose content and hemicellulose content both showed positive relationships with seedling quality (r=0.907, r=946, P=0.01, P=0.05, respectively). Taken together, these findings indicate that TOC, the C/N ratio, $NH_4^+$-N, $NO_3^-$-N, AK and lignocellulose content can be used to evaluate compost maturity.

## 4. Conclusion

In this study, the BR and SMS were composted for 118 days and the maturity of compost were determined by seedling cultivation, after which physical and chemical indexes related to maturity were analyzed by correlational analysis and other methods. Taken together, the findings presented in this study show that TOC, C/N ratio, $NH_4^+$-N, $NO_3^-$-N, AK and lignocellulose content can be used to evaluate compost maturity. However, because the seedling cultivation cycle takes more than 30 days, more researches were needed to acquire a feasible method for determining compost maturity.

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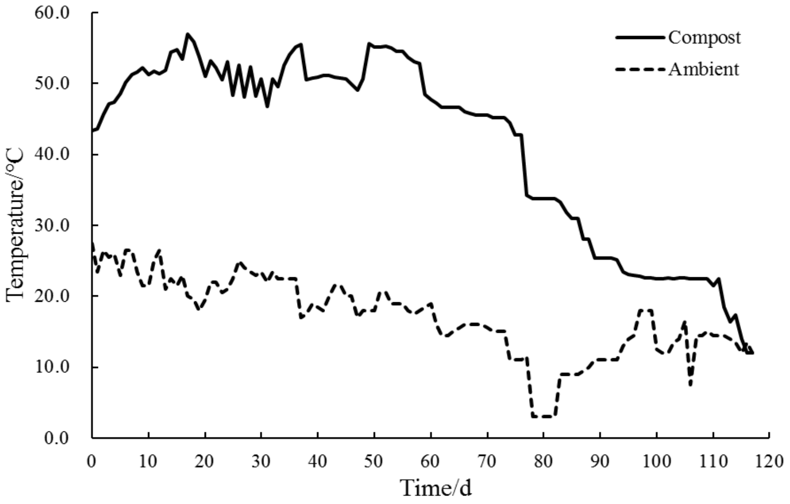

Fig. 1. Changes of pile temperatures during the composting process.

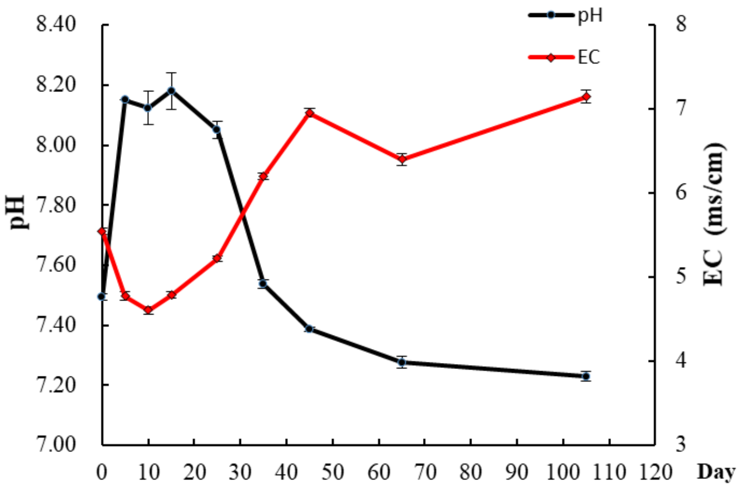

Fig. 2. Changes of pH and EC during the composting process

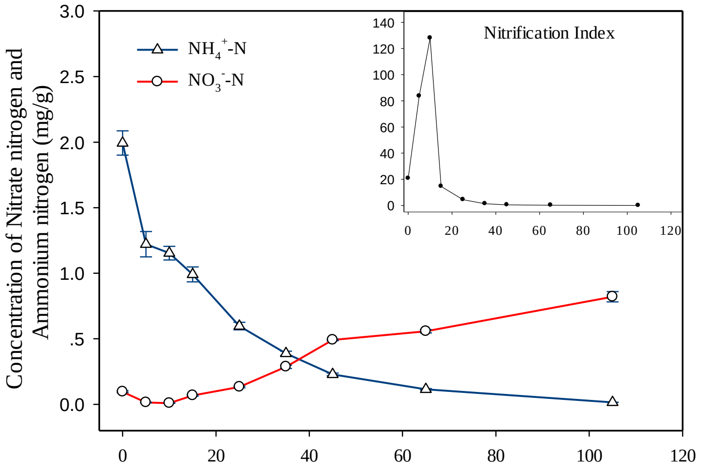

Fig. 3. Concentration of Nitrate nitrogen, Ammonium nitrogen and Nitrification Index during the composting process

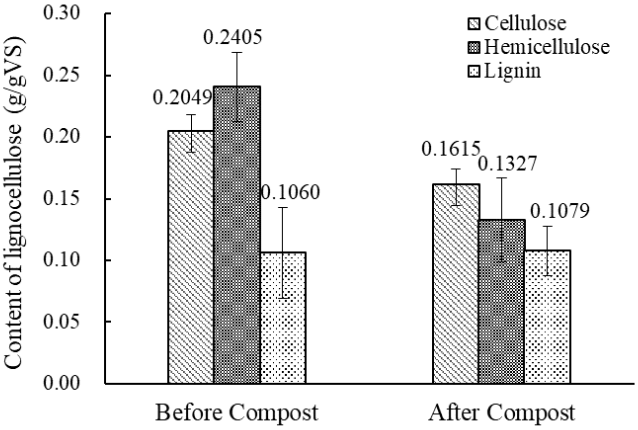

Fig. 4. Content of lignocellulose before and after compost process

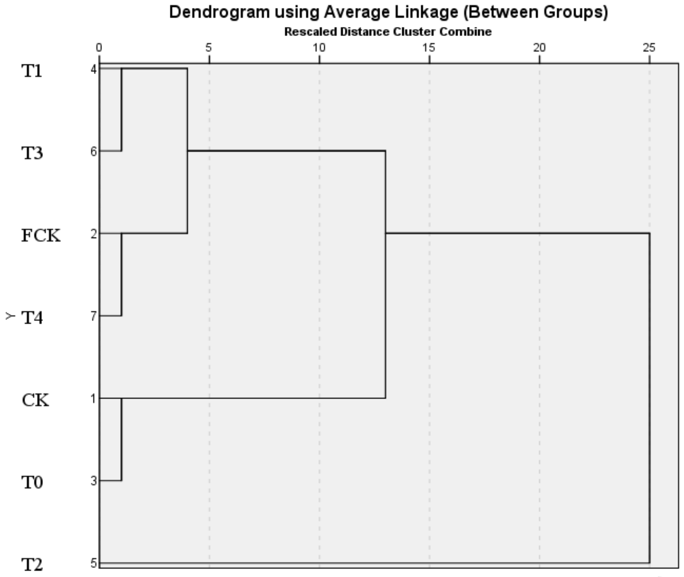

Fig. 5Hierarchical cluster analysis of the treatments tested in the present study, based on the substrate properties and plant variables (CK: peat without fertilizer; F-CK peat+fertilizerT1; T0: raw material of SMS+BR; T1: 100% compost; T2: 80% compost; T3: 50% compost; T4: 20% compost)

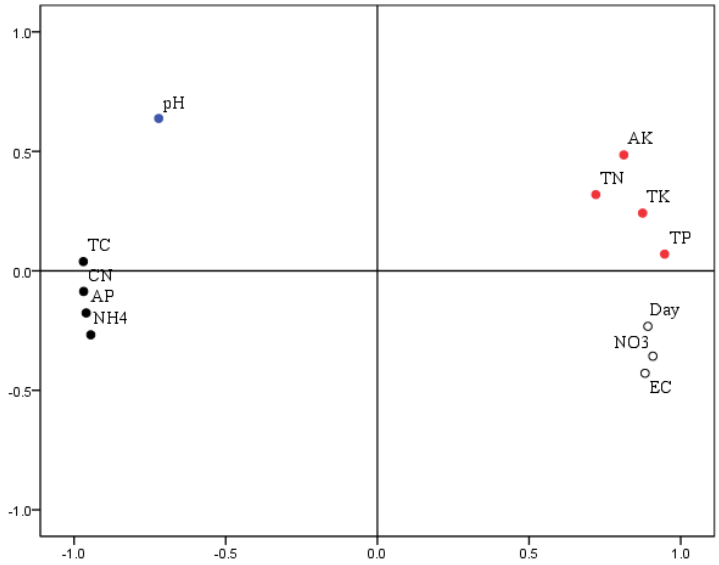

Fig. 6. PCA analysis of the parameters in composting process

Table 1 The treatments of the seedling substrates.

| | F-CK | CK | T0 | T1 | T2 | T3 | T4 |
|---|---|---|---|---|---|---|---|
| Fertilize | √ | × | × | × | × | × | × |
| Perlite | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Raw Material | | | 5 | | | | |
| Compost | | | | 5 | 4 | 2.5 | 1 |
| Peat | 5 | 5 | | | 1 | 2.5 | 4 |

All the material were mixed in v:v;
F-CK was fertilized in commercial method.

Table 2 Characteristics of physical-chemical during composting

| **Day** | **TOC (mg/g)** | **TN (%)** | **C/N** | **TK (%)** | **TP (%)** | **Available Potassium (mg/g)** | **Available Phosphorus (mg/g)** |
|---|---|---|---|---|---|---|---|
| 0 | 385.526±4.015 | 1.961±0.050 | 19.667±0.416 | 1.063±0.015 | 1.716±0.041 | 11.957±0.208 | 2.010±0.074 |
| 5 | 380.144±12.469 | 2.041±0.039 | 18.615±0.917 | 1.113±0.015 | 1.692±0.022 | 16.233±0.296 | 1.877±0.080 |
| 10 | 399.505±7.478 | 1.994±0.075 | 20.036±1.094 | 1.127±0.021 | 1.735±0.030 | 16.153±0.329 | 1.676±0.047 |
| 15 | 352.595±0.435 | 2.057±0.034 | 17.147±0.273 | 1.143±0.025 | 1.863±0.042 | 16.747±0.021 | 1.416±0.063 |
| 25 | 330.299±7.543 | 2.099±0.028 | 15.731±0.434 | 1.187±0.015 | 1.934±0.038 | 17.060±0.132 | 1.110±0.030 |
| 35 | 311.755±5.498 | 2.130±0.024 | 14.640±0.435 | 1.207±0.023 | 1.974±0.061 | 18.197±0.310 | 0.903±0.064 |
| 45 | 304.756±9.574 | 2.228±0.041 | 13.691±0.539 | 1.300±0.010 | 2.056±0.020 | 17.877±0.015 | 0.836±0.031 |
| 65 | 300.579±0.356 | 2.311±0.051 | 13.035±0.278 | 1.203±0.012 | 1.981±0.008 | 18.613±0.321 | 0.749±0.099 |
| 105 | 277.995±7.211 | 2.051±0.056 | 13.569±0.592 | 1.217±0.012 | 2.053±0.016 | 18.610±0.160 | 0.815±0.052 |

Table 3 Synthetical evaluation on seedling quality of tomato in different media

| Treatment | leaf Number | Height/cm | Stem diameter/mm | Ground fresh weight/g | Ground dry weight/g | Underground fresh weight/g | Underground dry weight/g | Total dry weight/g | Leaf area/cm$^2$ | CEC |
|---|---|---|---|---|---|---|---|---|---|---|
| CK | 0.19 | 0.11 | 0.21 | 0.13 | 0.07 | 0.23 | 0.15 | 0.09 | 0.05 | 0.14 |
| F-CK | 0.65 | 0.23 | 0.36 | 0.35 | 0.21 | 0.37 | 0.37 | 0.24 | 0.24 | 0.34 |
| T0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| T1 | 0.91 | 0.88 | 0.92 | 0.93 | 0.70 | 0.73 | 0.63 | 0.69 | 0.82 | 0.80 |
| T2 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| T3 | 0.77 | 0.47 | 0.69 | 0.76 | 0.70 | 0.66 | 0.56 | 0.68 | 0.56 | 0.65 |
| T4 | 0.53 | 0.26 | 0.48 | 0.46 | 0.42 | 0.59 | 0.35 | 0.41 | 0.46 | 0.44 |

CEC: Comprehensive Evaluation Coefficient

Table 4 Spearman correlation among physical-chemical parameters during composting process

| | Day | TOCmg/g | pH | EC | NH$_4$mg/g | NO$_3$mg/g | TK% | TN% | TP% | AKmg/g | APmg/g | C/N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | 1 | -0.923$^{**}$ | -0.702 | 0.781 | -0.991$^{**}$ | 0.879$^{*}$ | 0.873$^{*}$ | 0.687 | 0.904$^{**}$ | 0.952$^{**}$ | -0.952$^{**}$ | -0.926$^{**}$ |
| TOCmg/g | | 1 | 0.745 | -0.893$^{*}$ | 0.929$^{**}$ | -0.935$^{**}$ | -0.847$^{*}$ | -0.673 | -0.896$^{*}$ | -0.901$^{**}$ | 0.856$^{*}$ | 0.937$^{**}$ |
| pH | | | 1 | -.0919$^{*}$ | 0.693 | -0.887$^{*}$ | -0.584 | -0.400 | -0.682 | -0.658 | 0.662 | 0.684 |
| EC | | | | 1 | -0.789$^{*}$ | 0.945$^{**}$ | 0.713 | 0.542 | 0.808$^{*}$ | 0.740 | -0.716 | -0.802$^{*}$ |
| NH$_4$mg/g | | | | | 1 | -0.873$^{*}$ | -0.867$^{*}$ | -0.713 | -0.897$^{*}$ | -0.948$^{**}$ | 0.940$^{**}$ | 0.935$^{**}$ |
| NO$_3$mg/g | | | | | | 1 | 0.748 | 0.602 | 0.846$^{*}$ | 0.849$^{*}$ | -0.847$^{*}$ | -0.878$^{*}$ |
| TK% | | | | | | | 1 | 0.721 | 0.903$^{**}$ | 0.861$^{*}$ | -0.861$^{*}$ | -0.841$^{*}$ |
| TN% | | | | | | | | 1 | 0.681 | 0.715 | -0.756 | -0.843$^{*}$ |
| TP% | | | | | | | | | 1 | 0.840$^{*}$ | -0.858$^{*}$ | -0.868$^{*}$ |
| AKmg/g | | | | | | | | | | 1 | -0.934$^{**}$ | -0.924$^{**}$ |
| APmg/g | | | | | | | | | | | 1 | 0.906$^{**}$ |
| C/N | | | | | | | | | | | | 1 |

*:Correlation is significant level at 0.05.

**: Correlation is significant level at 0.01.

Table 5 Spearman correlation of CEC with physical and chemical growth media

| | pH | EC | TOC | TN | C/N | AP | AK | Cellulose | Hemicellulose | Lignin |
|---|---|---|---|---|---|---|---|---|---|---|
| CEC | 0.449 | -0.382 | -0.628 | 0.491 | -0.885* | 0.679 | -0.857* | 0.907* | 0.946** | -0.948** |
| P value | 0.313 | 0.404 | 0.083 | 0.042 | 0.019 | 0.092 | 0.014 | 0.012 | 0.005 | 0.005 |

*:Correlation is significant level at 0.05.

**: Correlation is significant level at 0.01.

Highlights

Composting of biogas residues and spent mushroom substrate lasted 118 days.

Plant growth was used to evaluate the compost maturity.

Compost as tomato substrate showed better seedling quality than commercial seedling.

TOC, C/N, $NH_4^+$-N, $NO_3^-$-N, AK and lignocellulose can be used to evaluate compost maturity.