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# Nitrogen transformations during co-composting of herbal residues, spent mushrooms, and sludge*

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**Abstract:** Sewage sludge composting is an important environmental measure. The reduction of nitrogen loss is a critical aim of compost maturation, and the addition of spent mushrooms (SMs) and herbal residues (HRs) may be helpful. To evaluate the nitrogen transformations during co-composting of sewage sludge, SMs, and HRs, windrows were constructed in a residual processing plant. Dewatered sewage sludge and sawdust were mixed with SMs and HRs at two proportions on a fresh weight basis, 3:1:1 (sewage sludge:sawdust:SMs or HRs) and 3:1:2 (sewage sludge:sawdust:SMs or HRs). The mixture was then composted for 40 d. Changes in the physicochemical characteristic of sewage sludge during composting were recorded and analyzed. Addition of SMs and HRs accelerated the temperature rise, mediating a quicker composting maturation time compared to control. The addition also resulted in lower nitrogen losses and higher nitrate nitrogen levels in the compost products. Among the windrows, SM and HR addition improved the nitrogen status. The total nitrogen (TN) and nitrogen losses for SM and HR treatments ranged from 22.45 to 24.99 g/kg and from 10.2% to 22.4% over the control values (18.66–21.57 g/kg and 40.5%–64.2%, respectively). The pile with the highest proportion of SMs (3:1:2 (sewage sludge:sawdust:SMs)) had the highest TN level and the lowest nitrogen loss. The germination index (GI) values for all samples at maturity were above 80%, demonstrating optimal maturity. The addition of SMs and HRs augments sewage composting.

**Key words:** Sewage sludge, Spent mushrooms, Herb residues, Maturity, Nitrogen retention, Co-compost
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## 1 Introduction

Recently, with the continuous expansion of sewage processing plants, the amount of city sewage sludge has become a serious environmental menace (Ma *et al*., 2003). Sewage sludge contains abundant organic matter and some nutrients like nitrogen (N), phosphorus (P), and potassium (K), which can be employed for enhancing crop productivity after composting. To accomplish the composting process rapidly, some auxiliary materials, such as sawdust, are required to act as conditioner; however, the use of sawdust is becoming increasingly limited due to its limited availability and rising market prices.

At present, the amount of spent wastes such as spent mushrooms (SMs) and herb residues (HRs) is ever increasing in China, both of which could act as an alternative to sawdust during composting of sewage sludge. The SMs and HRs are rich sources of nutrients such as organic substances, N, P, K, etc. Being light-weight media after crushing, they act as superior auxiliary materials.

Waste co-composting not only reduces solid wastes, but also enhances the compost quality by the comprehensive usage of diversified material properties (Fang and Wong, 1999).

The N content in compost is one of the critical indices for determining composting quality (Goldstein and Steuteville, 1993). A multi-component

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modeling system has been developed to simulate substrate degradation and oxygen consumption in waste composting processes (Lin *et al*., 2008b). A simulation-aided two-level factorial analysis approach has been proposed to characterize the interactive effects of composting factors (i.e., temperature, moisture, oxygen content, and initial biomass concentration) on composting processes (Lin *et al*., 2008a). However, many researchers have pointed out the considerable nitrogen losses during the course of composting (Kirchmann and Witter, 1989; Eklind and Kirchmann, 2000). The nitrogen losses caused by the evaporation of ammonia nitrogen and the denitrification of nitrate nitrogen reached 43%–70% over and above the leaching loss, the total losses reaching 77% (Martins and Dewes, 1992). According to Steniford (1987), the compost quality produced through traditional compost technology was inferior and nearly without application in the market, as the compost technology did not emphasize the nutritional values, particularly that of N. Therefore, the key to the development of compost technology is to control the changes and the nitrogen losses, and this has attracted the attention of many compost researchers (Cordovil *et al*., 2007; Meijide *et al*., 2007).

At present, the nitrogen loss prevention technology in compost mainly focuses on the following aspects: firstly, reducing nitrogen losses by adjusting the carbon to nitrogen (C/N) proportion (Lhadi *et al*., 2004; Meijide *et al*., 2007); secondly, reducing nitrogen losses by manipulating the temperature changes (Hiraku *et al*., 2004); thirdly, exploiting the properties of compost materials and adjusting the properties of filling absorption, porosity, and moisture content through material proportion (Kirchmann and Witter, 1989; Ekinci *et al*., 2002). Currently, research on sewage sludge compost is mainly focused on the first two aspects. The present study aimed to improve the properties of product compost and to reduce the nitrogen loss during composting of sewage, SMs, and HRs.

## 2 Materials and methods

### 2.1 Raw materials

All experiments were conducted in Zhejiang Luyuan Organic Nutrient Soil Company, Zhejiang, China. The sludge used in the experiment was dewatered sludge generated from Fuyang Wastewater Treatment Plant located in Fuyang County, Zhejiang Province, China. The SMs were taken from a company producing Agrocybe in Hangzhou. The HRs were provided by Hu Qing Yu Chinese Pharmacy in Hangzhou, Zhejiang, China. The sawdust was waste material from a wood processing factory in Fuyang County. The main characters of raw materials are shown in Table 1.

**Table 1 Selected physicochemical parameters of raw materials**

| Raw materials | MC (%) | OC (g/kg) | TN (g/kg) | pH | EC (dS/m) |
|---|---|---|---|---|---|
| Sludge | 80.50 | 278.03 | 49.02 | 7.59 | 0.35 |
| Sawdust | 20.64 | 404.21 | 12.50 | 6.10 | 0.07 |
| SMs | 64.25 | 256.86 | 29.32 | 7.71 | 0.47 |
| HRs | 54.62 | 335.31 | 32.80 | 6.42 | 0.36 |

SMs: spent mushrooms; HRs: herbal residues; MC: moisture content; OC: organic carbon; TN: total nitrogen; EC: electrical conductivity

### 2.2 Composting procedure

Raw materials were blended in the proportions as described in Table 2 and were piled up in a windrow pyramid, which was 1.5 m high, 2 m wide, and 4 m long in a vinyl chamber having a height of 50 m and a width of 20 m. Pile turning was administered to ensure oxygen supply. Pile turning and sampling were carried out on Days 0, 3, 7, 10, 14, 17, 21, 28, 38, and 40. Four section planes were selected at regular intervals for sampling in longitudinal direction of each pile. During the course of pile turning, five sampling and mixing points were selected in each section plane. The weight of each sample was about 500 g. Cold water was added in the compost chamber to control the moisture content in the range of 65%–70%, as 35% water loss occurred through natural evaporation at maturity stage if water was not added.

### 2.3 Analytical methods

Temperature determination was made daily using a mercury thermometer at depths of 20, 50, and 70 cm from the top of the pyramid. Electrical conductivity (EC) and pH determination were done by mixing deionized water with the samples in the proportion of 1:10 (w/v), the mixture being shaken for 2 h, and then an ion electrode method being used to

**Table 2 Mixture ratio of compost and its physicochemical parameters**

| Processing | Component material | Wet weight ratio | TN (g/kg) | C/N | pH | EC (dS/m) | MC (%) |
|---|---|---|---|---|---|---|---|
| CK1 | Sludge | 100% | 49.02 | 5.67 | 7.59 | 0.34 | 81 |
| CK2 | Sludge+sawdust | 3:1 | 22.32 | 16.41 | 7.33 | 0.29 | 71 |
| G1 | Sludge+sawdust+SMs | 3:1:1 | 23.62 | 14.66 | 7.50 | 0.48 | 70 |
| G2 | Sludge+sawdust+SMs | 3:1:2 | 24.07 | 13.73 | 7.66 | 0.36 | 69 |
| Y1 | Sludge+sawdust+HRs | 3:1:1 | 24.51 | 14.49 | 7.43 | 0.25 | 70 |
| Y2 | Sludge+sawdust+HRs | 3:1:2 | 25.76 | 13.55 | 7.24 | 0.32 | 68 |

CK1 and CK2 are the controls while G1, G2, Y1, and Y2 are the treatments. TN: total nitrogen; C/N: carbon to nitrogen ratio; EC: electric conductivity; MC: moisture content; SMs: spent mushrooms; HRs: herbal residues

measure the EC and pH values of the samples after centrifugation at 10000 r/min. Organic carbon was determined by the potassium dichromate wet air oxidation method (APHA, 2005). Total nitrogen (TN) was measured by the semi-micro Kjeldahl method while ammonia nitrogen determination was carried out according to the indophenol blue colorimetric method (APHA, 2005). Nitrate nitrogen was determined following the Fe-Zn reduction method (Bao, 2005). Moisture content determination was carried out by drying the samples at 105 °C for 24 h. Germination index (GI) was measured by culturing 50 cress seeds in the culture vessel containing 5.0 ml composting extract solution for 24 h, maintaining deionized water for the blank seeds, and then calculating the ratios of the GI product and root length of the processed seeds to those of the blank seeds (Zucconi *et al.*, 1981). The statistical analysis was performed by Data Processing System software.

## 3 Results and discussion

### 3.1 Temperature regulation and pH changes

Temperature is a critical factor influencing the microbial activity, ordinarily considered as the macro-index of microbial biochemical activity during the process of composting (Peter, 1985; Zeng *et al.*, 2006). The increase in temperature during composting is caused by the energy released by the catabolism accomplished by microorganisms. The changes in temperature during various stages of composting are shown in Fig. 1. Throughout the process, the temperature of control pile (CK1) increased with the progress of the compost period but still remained below 50 °C, which was 2–13 °C higher than ambient temperature over 40 d. On the 3rd day, the temperatures of G1, G2, Y1, and Y2 increased to 45, 48, 45, and 52 °C, respectively, and after the reaction at high temperature, the temperature of CK2 rose slowly to 45 °C on the 5th day. The period was characterized by high temperatures for CK2, G1, G2, and Y1, which lasted until the 17th day, and then the temperatures gradually reduced to the level of ambient temperature and finally entered the matured stage. The high temperature for Y2 lasted until the 28th day and then started to decline gradually until the 40th day. The temperature at the top during the process was over 60 °C. According to Peter (1985) the microbial diversity will be greatly reduced when the temperature was over 60 °C, which would impart a negative impact upon composting process. The initial carbon to nitrogen ratio (C/N) of CK2 was the highest (Table 2), and later on its values were lower than those of G1, G2, Y1, and Y2. Except for CK1, the highest temperature stage of other processes remained at 50 °C for at least 5 d, fulfilling the composting sanitation requirements of China (GB 7959-87).

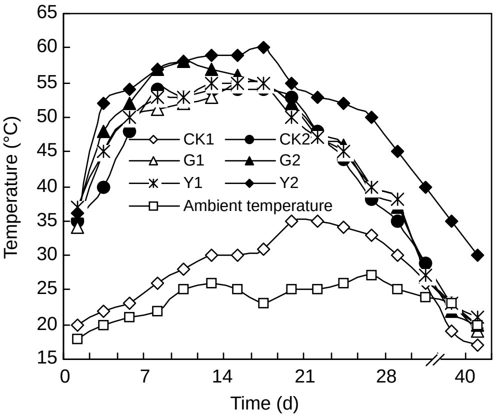

**Fig. 1 Change in temperature during co-composting process**

The present study showed that the addition of SMs and HRs had a positive impact on the composting process, causing an increase in the temperature. The addition of a higher amount of HRs to Y2 caused a higher temperature than the ambient temperature even after 40 d, which may increase nutrition losses.

The pH variations during the composting process are shown in Fig. 2. The variation trends for CK1, CK2, G1, G2, Y1, and Y2 were approximately similar, i.e., 7.93, 8.47, 8.66, 8.65, 8.54, and 8.39, respectively, on the 14th day. During the initial stages of composting, mineralization of organic matter occurred, in which organic nitrogen was converted to ammonia, causing a rise in the pH value in the later stages (Bishop and Godfrey, 1983). The alkalinity was reduced due to the decrease of pH during the volatilization and nitrification processes. Low molecular weight organic acid and inorganic acids released from the microbial degradation of organic matter may reduce the pH value (Eklind and Kirchmann, 2000). Moreover, the dissolution of carbon dioxide in aqueous medium would result in the reduction of pH value. Initially, the pH values of compost, from lower to higher, followed the sequence of Y2, CK2, Y1, G1, CK1, and G2, possibly due to the pH values of sawdust and HRs being lower than those of sewage sludge and SMs (Table 1). With the rise in the temperature of pile, the pH values ranged from 7.0 to 8.5, which was the optimal pH range for composting (Buijsman *et al.*, 1987; Dewes, 1996) that could reduce the volatilization speed of ammonia and the nitrogen losses.

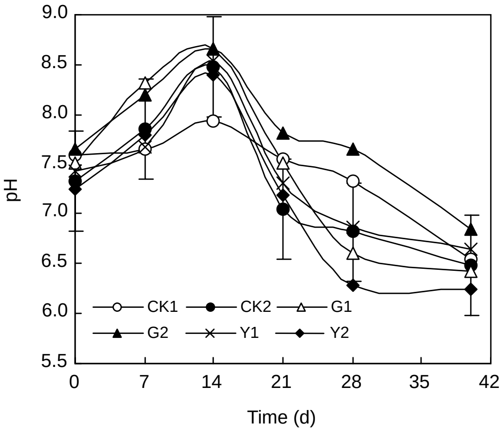

**Fig. 2 Change in pH during co-composting process**

## 3.2 Changes in organic carbon and carbon-nitrogen ratio

The changes in the organic carbon content reflect the microbial-induced degradation of organic matter. The changes of organic carbon during composting process are shown in Fig. 3. During the whole process, the organic carbon contents of CK1, CK2, G1, G2, Y1, and Y2 dropped from the initial values of 27.8%, 36.7%, 34.7%, 33.1%, 35.5%, and 34.9% to 20.9%, 28.2%, 30.9%, 29.2%, 29.4%, and 30.1%, respectively, after compost maturity. The decomposition rate of organic carbon was 24.6%, 23.2%, 10.9%, 11.6%, 17.1%, and 13.8% for CK1, CK2, G1, G2, Y1, and Y2 treatments, respectively. Based on loss rates, various treatments can be listed as G1<G2<Y2<Y1<CK2<CK1. That is, adding different proportions of SMs and HRs not only effectively reduced the carbon losses, but could also reduce the use of sawdust and maintain the fertility of compost.

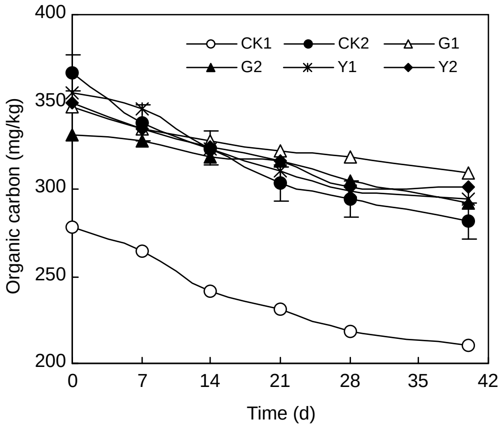

**Fig. 3 Change in organic carbon during co-composting process**

The study of Wong *et al.* (1996) showed that the carbon losses were only 9% (the proportion of the municipal sewage sludge and sawdust mixed in the compost was 2:1 (w/w), the initial carbon to nitrogen (C/N) ratio was 25, and the organic carbon content of final product was 34%), much lower than those in our research. This may be due to losses caused by pile turning for oxygen supply, a problem that may be associated with pile turning frequency.

The changes in C/N ratio showed that the C/N ratios of all treatments declined rapidly, with the exception of CK1, for which this parameter increased (Fig. 4). The descending rates of C/N ratio in CK2, G1, G2, Y1, and Y2 were 19.1%, 11.1%, 14.9%, 17.9%, and 13.5%, respectively. It seemed that mesophile microorganisms released heat through degradation of organic matter during the earlier stages of composting reaction and the windrow pyramid reached the pyrolysis stage quickly. Then the thermophilic microorganisms began to predominate when the temperature of the pile exceeded 45 °C, and they continued to utilize dissolved organic matter, which mainly consisted of decomposed cellulose, hemicelluloses, lignin, as well as other difficult-to-break-down organic matter (Zeng *et al*., 2006). The nitrogenous organic matter mainly decomposed through an ammonifying process. The increased pH and ammonia nitrogen concentration would support this hypothesis (Figs. 2 and 6). However, there was little volatilization when pH of ammonified product was lower than 8.5. During initial stages of composting, the metabolic carbon utilization was much higher than that of nitrogen, which might have caused a decrease in C/N ratio. Although, whole organic matter was almost decomposed into humus by the microbial activity, still some organic matter was comparatively difficult or very difficult to decompose during later stages, whereby the thermophilic microorganisms stopped growth, as indicated by alleviated degradation speed due to lack of proper nutrition. Afterwards, the mesophilic microorganisms again became dominant as the residual organic matter caused continual humification reorganization while being decomposed. This stabilized the pile, and the carbon reduction in this stage was slower (Zeng *et al*., 2006). During later stages of composting, C/N ratio became stable and even increased slightly. Without any conditioner the initial C/N ratio of CK1 was low enough to speed up the nitrogen loss, which slowed down the carbon degradation, thus increasing C/N ratio.

### 3.3 Nitrogen dynamics

TN includes both organic nitrogen and inorganic nitrogen (mainly ammonia nitrogen and nitrate nitrogen, partly dissolved $NO_2$ in liquid phase) which are normally assimilated by microbes. The variations of TN for different treatments are shown in Fig. 5. Except for CK1, the TN of other piles reached their maximum on the 14th day, and then decreased gradually as the composting time increased until maturity. The initial value of TN for CK1 without any conditioner was the highest, but it reduced drastically over time. This was possible due to the nitrogen in the sludge being mainly ammonia nitrogen with a high pH value. This was able to drain with the percolating liquid (Table 1, Fig. 6) and was volatilized as ammonia. The decrease in organic matter content reduced the sizes of the piles and the nitrogen loss rates were lower than the carbon degradation rates, resulting in lower C/N ratio as TN was concentrated (Inoko *et al*., 1979; Fang and Wong, 1999). The minimal decline of TN in the later stage of reaction was mainly caused by the volatilization of ammonia (Fang and Wong, 1999; He *et al*., 2007), as well as denitrification of anaerobic bacterial domains and leaching of soluble nitrogen forms. In addition, nitrifying bacteria also contributed to TN in the later stage of reaction (Bishop and Godfrey, 1983). The final TN contents of CK1, CK2, G1, G2, Y1, and Y2 were 21.57, 18.66, 22.45, 24.99, 24.75, and 24.21 g/kg, respectively. According to nitrogen loss rate calculation by Cao *et al*. (2004), the nitrogen loss rates were 64.2%, 40.5%, 18.3%, 10.2%, 20.7%, and 22.4%, for CK1, CK2, G1, G2, Y1, and Y2, respectively.

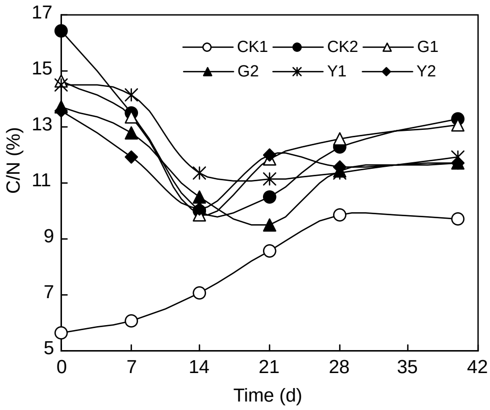

**Fig. 4 Change in C/N ratio during co-composting process**

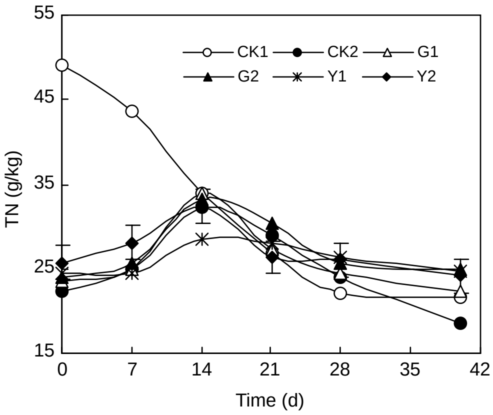

**Fig. 5 Change in TN during co-composting process**

The nitrogen preservation effects of co-composting with SMs or HRs are much better than that of control. The nitrogen losses of the co-composting were lower than those of sludge compost with straw and leaves (31%–34%) (He *et al.*, 2007). The nitrogen losses of compost were significantly reduced by the addition of SMs or HRs. The addition of 20% SMs and HRs might impart obvious effects on nitrogen preservation. However, prolonged high reaction temperatures accelerated the volatilization of ammonia nitrogen, and consequently the nitrogen loss of Y2 with higher dose of HRs was larger than those of other treatments.

The variations in ammonia-nitrogen are shown in Fig. 6. The ammonia nitrogen content of the piles increased at first and then decreased during the composting process. The ammonia nitrogen content increased rapidly during the first week, reaching the maximum in about 10 d, and then after a slow decline it decreased rapidly after four weeks until compost was mature. The rapid rise during the initial stage was mainly due to mineralization and ammonification processes accompanied by the decomposition of organic matter (Fang and Wong, 1999), so the concentration of ammonia nitrogen reached its maximum value. During humification, mineralized nitrogen and organic matter were recombined into humus. The nitrogen loss was mainly due to the nitrification during pile turning, which could have caused the emission of some nitrogen oxides. The enhancement of nitrification and the continuous volatilization of ammonia reduced the ammonia nitrogen content (Fig. 7). The concentration of ammonia nitrogen declined rapidly after four weeks because of the enhanced humification. The stability of TN would support this point of view (Fig. 5). The final ammonia nitrogen contents of CK1, CK2, G1, G2, Y1, and Y2 were 0.49, 0.59, 0.61, 0.31, 0.96, and 0.73 g/kg, respectively. It is generally believed that decline in ammonia nitrogen concentration is a sign of compost maturity (Morisaki *et al.*, 1989; Bernai *et al.*, 1998). Zucconi *et al.* (1981) recommended that compost could be considered mature if the concentration of ammonia nitrogen was less than 430 mg/kg. For instance, Fang and Wong (1999) studied co-compost containing sludge, sawdust, and fly ash, in which the ammonia nitrogen content of mature compost reached 700 mg/kg. In our study, only G2 satisfied the standard presented by Zucconi *et al.* (1981). This result indicated that the SM addition in G2 relatively benefited the compost maturity. The lower initial C/N ratio of other treatments, which was 15, resulted in higher ammonia nitrogen content. Thus, operating conditions and properties of raw materials have a greater influence upon the ammonia nitrogen content, which can serve as a reference indicator of compost maturity.

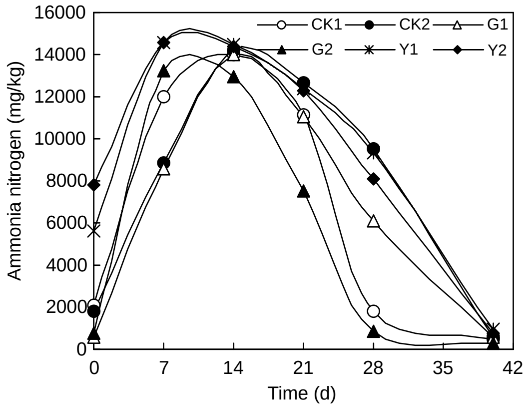

**Fig. 6 Change in ammonia nitrogen during co-composting process**

The changes in nitrate nitrogen through the study period were shown in Fig. 7. The concentration of nitrate nitrogen continued to increase throughout the composting time. The nitrate nitrogen content was about zero initially, which kept on increasing as the reaction proceeded until compost maturity. The overall nitrate nitrogen content was high and its maximum was only about 700 mg/kg. Because heat and excessive ammonia nitrogen mostly decreased the nitrifying bacterial activity, nitrate nitrogen content was relatively low in the earlier stages of composting (Morisaki *et al.*, 1989; Huang *et al.*, 2004). Higher pH may also inhibit the growth of nitrifying bacteria to slow the incremental addition of nitrate nitrogen (Pichtel, 1990). After 14 d, as the inhibition caused by high temperature, high ammonia nitrogen, and high pH was reduced, the nitrification was enhanced, and the nitrate nitrogen content also increased (He *et al.*, 2007). Under the stable conditions, the nitrate nitrogen contents of CK1, CK2, G1, G2, Y1, and Y2 were 0.17, 0.57, 0.64, 0.61, 0.44, and 0.45 g/kg, respectively (G1>G2>CK2>Y2>Y1>CK1). Thus, the addition of SMs could promote nitrification; it was possible that temperature reduction was rapid in this process. However, HR addition initially slowed down the nitrification of compost due to higher produced temperature and its longer duration. In the CK1, the initial C/N ratio was low with high moisture content. Inadequate oxygen supply may have suppressed nitrification, which led to the lowest nitrate nitrogen content.

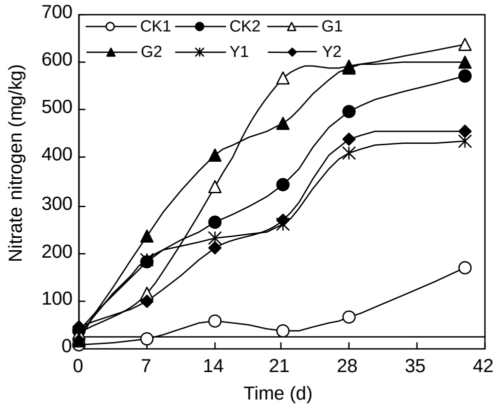

**Fig. 7 Change in nitrate nitrogen during co-composting process**

The regression equations for TN, nitrate nitrogen, and ammonia nitrogen are shown in Table 3, indicating that, with the exception of Y2 and CK1, the correlation of TN with water-soluble inorganic nitrogen was not significant in the remaining treatments. Thus, the role played by organic nitrogen should not be neglected. Hu *et al.* (2004) considered that the water-soluble nitrogen in compost materials consisted of ammonia nitrogen and nitrate nitrogen. This aspect of the study should be further verified.

## 3.4 Compost maturity analysis

Due to the complexity of compost materials, the maturity assessment of the compost product generally requires a variety of indicators for integrated testing. The studies of Huang *et al*. (2004) indicated that solid phase and water-soluble C/N ratios were only suitable indicators for evaluating compost maturity. Low C/N ratio was not appropriate. Temperature, pH, and ammonia nitrogen content can only serve as reference to instruct the composting reaction process. It is generally believed that the GI is one of the most accurate biological indicators to reflect the compost maturity. It has fully demonstrated the accumulation of toxic effects in seeds caused by various toxic substances (Hirsch, 1998; Zhou, 2006). Zucconi *et al.* (1981) believed that compost was supposed to be mature when GI exceeded 80%. The GI values obtained during the present experiment are shown in Fig. 8. The GI of CK1 was less than 40%, which signifies that the compost containing sludge alone is not mature after 40 d of composting. The GI values of all other treatments were above 80%. The GI of G2 was the highest, pointing to an optimal maturity. It was proved that the SM addition in G2 could promote compost maturity.

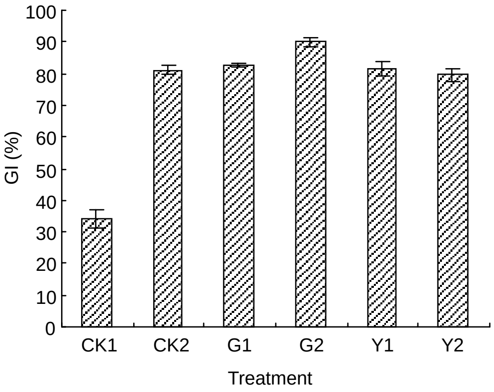

**Fig. 8 Variation of Germination index (GI) of different treatments**

**Table 3 Regression equations of TN, nitrate nitrogen, and ammonia nitrogen during co-composting**

| Processing | Component material | Equation | Significance level |
|---|---|---|---|
| CK1 | Sludge | $y$=54559.76+0.700$X_1$−145.893$X_2$ | 0.02 |
| CK2 | Sludge+sawdust | $y$=24.758+0.000892$X_1$−0.044$X_2$ | 0.08 |
| G1 | Sludge+sawdust+SMs | $y$=16297.57+0.552$X_1$−0.105$X_2$ | 0.11 |
| G2 | Sludge+sawdust+SMs | $y$=32472.67+0.094$X_1$−10.152$X_2$ | 0.15 |
| Y1 | Sludge+sawdust+HRs | $y$=31085.69−0.284$X_1$−2.514$X_2$ | 0.16 |
| Y2 | Sludge+sawdust+HRs | $y$=40261.91−0.585$X_1$−12.205$X_2$ | 0.02 |

$y$ (mg/kg): TN; $X_1$ (mg/kg): ammonia nitrogen content; $X_2$ (mg/kg): nitrate nitrogen content. SMs: spent mushrooms; HRs: herbal residues

## 4 Conclusions

All piles, except control, reached maturity stage in about 40 d. The addition of SMs and HRs raised sludge temperature, resulting in rapid compost maturity with lower C/N ratio. The ammonia nitrogen content increased rapidly in the first 10 d to a maximum, and then gradually decreased towards compost maturity. The ammonia nitrogen content of the compost with SMs was less than that of the compost with HRs, but its nitrate nitrogen concentration was greater than that of the latter. The nitrate nitrogen content increased throughout composting process. During the process, the TN of the compost with SMs and HRs was greater than that of the control treatment CK2. The nitrogen loss was 10.2%–22.4% which was also lower than that of CK2 (40%). The present results demonstrate that the loss rate of organic carbon exceeded 9%, which may be due to losses caused by pile turning for oxygen supply. The GI values for all samples at maturity were above 80%, pointing to an optimal maturity, with the exception of CK1. The best results were obtained using sludge:sawdust:SMs ratio of 3:1:2 (w/w/w) where the nitrogen loss was only 10.2% with TN value of 24.99 g/kg.

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