Initial Active Phase of In-Vessel Composting of Sewage Sludge, Leaves and Rice Straw

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ABSTRACT

This work studied the characteristics of leaf, rice straw, and sewage sludge (SS) co-composting with the aim of determining the best composting ratio by monitoring temperature changes, oxygen (O_2) concentration, carbon dioxide (CO_2) concentration, ammonia (NH_3) concentration, hydrogen sulfide (H_2S) concentration, pH, electrical conductivity (EC), heavy metal content, carbon-nitrogen ratio (C/N ratio), germination index (GI), moisture content (MC), and volatile solids (VS) content during the composting process. Three composting piles with the mixture ratios of 4:1:1 (Pile A), 5:1:1 (Pile B), and 6:1:1(Pile C) (SS: leaf: rice straw) were tested. According to the temperature, C/N ratio, germination index, MC, and VS, the level of compost maturity in Pile B with a 5:1:1 mixing ratio was higher than that in Piles A and C. The contents of heavy metals in the composts were shown to meet the grade A standard in CJ/T 309-2009 (2009), except Cu and Zn, which was within the grade B standard.

INTRODUCTION

With the development of urban landscaping and agriculture, green waste (garden waste and agricultural waste) production has increased in China. The annual amount of garden waste reached approximately 2.0×10^7 tons in China. Generally, green waste is incinerated or deposited in landfills in China (Zhang & Sun 2014). The average annual agricultural residue yield reached 5.2×10^8 tons during 2002-2011, approximately 19% of which was burned openly (Yang et al. 2015). Given the rapid increase of urban populations, SS has also continuously increased in the past twenty years. The annual amount of SS reached approximately 30,000,000 tons（Dai 2012). SS is mainly treated for landfills (30%) and agricultural use (45%) in China (Su et al. 2010). However, these treatments of SS have caused significant environmental perturbations, such as water and air and soil pollution (Dennehy et al. 2017). Therefore, it is critical to develop strategies to effectively recycle the wastes and alleviate environmental pollution meanwhile (Lu et al. 2009）

Green waste products are rich in fiber, protein, fat, and trace elements such as calcium (Ca), iron (Fe), copper (Cu), zinc (Zn), cobalt (Co), phosphorus (P), and manganese (Mn), among others. Previous research has shown that green waste composting can improve soil fertility and soil physical properties, maintain soil moisture levels, and prevent soil erosion (Tong et al. 2018). SS contains many soil nutrients such as organic matter (OM), nitrogen (N), phosphorus (P) and other micronutrients. However, using SS without prior stabilization has potentially negative effects on the remediation of degraded soils because they may contain phytotoxic or pathogenic substances, which have a highly unstable nature. One of the efficient techniques for treating and reusing organic waste is composting (Jayanta et al. 2021). The ratio of materials in the mixture is one of the key factors during composting. However, past research hasn't yielded a clear optimal ratio since the materials and composting circumstances differed. Banegas et al. (2007) recommended a 1:3 ratio (sludge: sawdust), based on the dilution effect caused by anaerobic sludge. Zubillaga & Lavado (2003) reported that the compost was not affected by the sawdust ratio. Lu

et al. (2009) recommended a 3:1:1 (v:v:v) mixture ratio of municipal solid waste: SS: mature compost in an in-vessel composting.

The aim of the present study is to examine the effects of the ratio of feedstock (i.e., leaf, rice straw, and SS) on the characteristics of the co-composting process and to obtain an optimum composting ratio based on the changes in temperature, O_2 concentration, CO_2 concentration, NH_3 concentration, H_2S concentration, pH, EC, heavy metal content, C/N ratio, GI, MC, and VS content during the composting process.

MATERIALS AND METHODS

Composting Materials

The dewatered SS with an MC of approximately 86.3% was obtained from the Qilidian Sewage Treatment Plant in Guilin City. The leaves (approximately 3.8% in MC) were collected from the Yanshan Botanical Garden in Guilin, whereas the rice straw (approximately 0.7% in MC) was collected from a rice farm in the Guilin Suburb. We chose leaves with sizes less than 100 mm and the whole leaves were used without cutting or grinding. A 9CFZ-40 feed grinder was used to cut the rice straw into small pieces of less than 40 mm. Table 1 shows the properties of the composting raw materials.

Experimental Set-up

The control technology for a bio-composting (CTB) system with intelligent real-time monitoring was used in this study. The system included three subsystems: three composting bioreactors, a real-time monitoring system, and the intelligent control system, as shown in Fig. 1. Each reactor was 1.3 m tall with a diameter of 0.8 m, and the effective volume was 250 L. The reactors had a double-cylinder structure and a polyethylene material was wrapped in an insulating layer. The monitoring system monitored composting parameters in the reactor in real-time and provided automatic feedback for controlling during the composting process. This system had a reaction chamber, a pump, gas flow meters, temperature probes, a CO_2 monitor, an H_2S monitor, an NH_3 monitor, an O_2 monitor and a control cabinet. Two groups of temperature probes were linked to the control cabinet and placed at a distance of 0.0 and 0.2 m from the composting reactor's cylindrical centerline. Each group of temperature probes was mounted 0.15, 0.3, 0.6, and 1.2 m above the bottom of the reactor to monitor the pile body temperatures at 1-min intervals. Each reactor installed four O_2 probes for monitoring the O_2 concentrations, which were mounted 0.2 m away from the cylindrical centerline of the composting reactor and 0.15, 0.3, 0.6, and 1.2 m above the bottom of the reactor. The CO_2, NH_3, and H_2S probes were connected to the exhaust collection tube to determine the CO_2, NH_3, H_2S concentrations. Temperature, as well as O_2, CO_2, NH_3, and H_2S concentrations, were recorded in the three reactors using the CTB automated control system and software (Compsoft 2.0; ZKBL Co., Ltd., China). The composting lasted for 300 h in this study.

Composting Methods

In this study, rice straw and leaves were cut into small pieces of less than 100 mm by a 9CFZ-40 feed grinder. The leaves and rice straw were mixed with SS by hand, using three mixing ratios, namely, Pile A, B, and C (4:1:1, 5:1:1, and 6:1:1, respectively; SS: leaf: rice straw, w:w:w). Table 2 shows the designs of the composting experiments and the main characteristics of the composting materials. The aeration rate was designed based on the pile's temperature during different composting stages (Table 3).

Sample Analysis

The solid and gas samples were analyzed during the composting process. The heavy metal content was determined by inductively coupled plasma emission spectrometry (IRIS Intrepid II XSP, Thermo Elemental Corporation, Franklin,
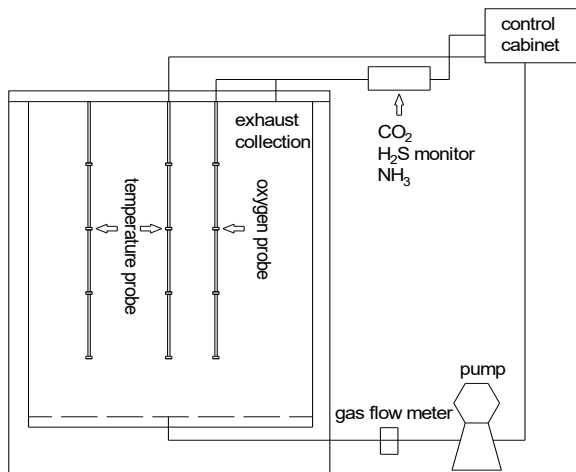

Fig. 1: Schematic of laboratory-scale composting device.

Table 1: The initial properties of raw materials.

Parameter	Sewage sludge	Leaf	Rice straw
Moisture content (%)	86.3 ± 1.7	7.9 ± 0.4	8.1 ± 0.26
Organic carbon (%)	46.56 ± 0.20	39.03 ± 0.38	39.49 ± 0.54
Total nitrogen (%)	4.80 ± 0.02	1.30 ± 0.01	1.06 ± 0.06
C/N Ratio	9.7 ± 0.07	30.1 ± 0.13	37.22 ± 2.3
TP (%)	1.09 ± 0.07	0.094 ± 0.018	0.08 ± 0.01
K (%)	0.61 ± 0.07	2.42 ± 0.66	2.22 ± 0.11
GI (%)	1.6 ± 0.5	60.1 ± 3.2	62.3 ± 4.7

Note: Reported values are mean ± STDEV of the three repeats

MA, USA). The GI was determined by the germination test（Sun et al. 2012a). The MC was analyzed by the weight loss after the sample was oven-dried at 105°C for 24 h. The VS content was determined by the additional weight loss after the sample was dried at 550°C for 4 h in a muffle furnace based on previously oven-dried weight. Other analytical methods involved in the protocol are shown in Table 4. The data was analyzed using SPSS 14.0 software. The differential analysis was used with the paired-sample *t*-test, and the bivariate correlation analysis was performed to analyze the relationship between the indexes.

RESULTS AND DISCUSSION

Changes in Temperature

The temperatures of the three composting piles of leaves, rice straw, and SS are shown in Fig. 2. The time-temperature curves at the central axis and edge of the bottom, lower-middle, middle, and surface layers in each reactor were different. The temperatures at the central axis of the reactor were higher than those at the edge. The temperatures at the lower-middle and bottom layers were higher than those at the middle and surface layers. The peak temperature reached 64.2, 62.2, and 65.9°C after 79, 78, and 46 h at the lower-middle layer in Piles A, B, and C respectively, while the peak temperature reached 59.2, 62.2, and 57.8°C after 71, 77, and 98 h at the bottom layer in Piles A, B, and C, respectively.

To meet the relevant composting requirements, the temperature needs to be maintained at above 55°C for at least 72 h or above 50-55°C for at least 120-168 h to kill pathogens (Chang et al. 2017，GB7959-2012 2012). Table 5 gives the highest temperature and the length of time each pile was over 50°C in both horizontal and vertical directions. In Pile A, the temperature at the central axis of the lower middle layer met the regulatory requirement for composting temperature, whereas, in Pile B and C, the temperatures at the center axis of the lower middle and bottom layers met the regulatory requirement. For Piles A, B, and C, the total time when the temperature was over 50°C was 240, 421, and 314 h, respectively. The temperature variations during the composting process indicated that the 5:1:1 ratio (SS: leaf: rice straw) gave the best performance in terms of maintaining a high temperature.

Changes in O_2 and CO_2 Concentrations

The changes in the O_2 consumption and CO_2 concentration are shown in Fig. 3. The O_2 consumption and CO_2 concentration increased as the temperature increased and they decreased as the temperature decreased. The lowest O_2 concentration was recorded at 72, 73, and 43 h in Piles A, B, and C, respectively, which was consistent with the appearance of the temperature peak (Fig. 2). The O_2 concentration was significantly different at the surface, middle, lower-middle, and bottom layers of the three piles. For the lower-middle layer, the O_2 concentration was not significantly different in Piles A and B ($P=0.562q$) but was significantly higher than that in Pile C ($P<0.01$). At the middle and surface layers, the O_2 concentration in Pile B was apparently lower than that

Table 2: Designs of the composting experiments.

Piles	Weight ratio	Quality [kg]	Volume [m³]	MC [%]	VS [%]
Pile A	4:1:1	46.2	0.245	63.7	82.23
Pile B	5:1:1	56.0	0.248	69.5	81.45
Pile C	6:1:1	60.0	0.250	73.0	80.20

Table 3: Designs of the aeration rate.

	The aeration rate [L.min⁻¹]		
	mesophilic phase	thermophilic phase	cooling phase
Pile A	6	4	6
Pile B	7	5	7
Pile C	8	6	8

Table 4: The main analytical project and methods.

Analysis items	Analytical methods and instruments	Instrument types
O_2	oxygen on-line monitor	I/-01, Shenzhen, China
NH_3	ammonia on-line monitor	MR-100/1000, Membrapor, Switzerland SwitzerlandChina
H_2S	hydrogen sulfide on-line monitor	M-100/500, Membrapor, Switzerland
CO_2	carbon dioxide on-line monitor	GM220, VAISALA, Finland
Temperature	temperature probe	PT100, Shenzhen, China
pH	portable pH meter	pH330, WTW, Germany
EC	conductivity meter	M280536, Beijing, China

in Piles A and C ($P<0.01$). The trend indicates that the O_2 utilization in Pile B was higher than that in other piles. Based on the examination of testing data for each pile, a substantial negative correlation ($r^2>0.83$, $P<0.01$) was discovered between CO_2 and O_2 concentrations.

Changes in NH$_3$ Concentration

The changes in NH_3 concentration over time are shown in Fig. 4. The NH_3 concentration in Pile C was higher than that in Piles A and B ($P<0.01$). NH_3 was detected at approximately 90, 40, and 20 h in Piles A, B, and C, respectively. Then the NH_3 concentration increased and reached the peak values of 19, 66, and 84 ppm in Piles A, B, and C at 164, 190, and 186 h, respectively. Therefore, controlling NH_3 emission at 160-190 h was important for odor minimization.

After 190 h, the NH_3 emissions decreased quickly in all the piles and reached almost 0 ppm in Pile A at the end of composting. In Pile B, the NH_3 emissions fluctuated between 20-30 ppm after 220 h until the end of composting. However, the NH_3 concentration in Pile C continued to increase after 225 h and reached 60 ppm at the end of composting. This trend may be due to localized anaerobic conditions caused by the higher SS ratio in Pile C. The anaerobic bacteria might use CO_2 as a carbon source and produce more NH_3. This hypothesis could be confirmed by the changes in CO_2 concentration (Fig. 3). The CO_2 concentration of the exhaust gas in Pile C was lower than that in Piles A and B. As a result, effective measures to avoid and regulate NH_3 contamination during composting with a high sludge ratio should be adopted. Some additives including exogenous microbes such as
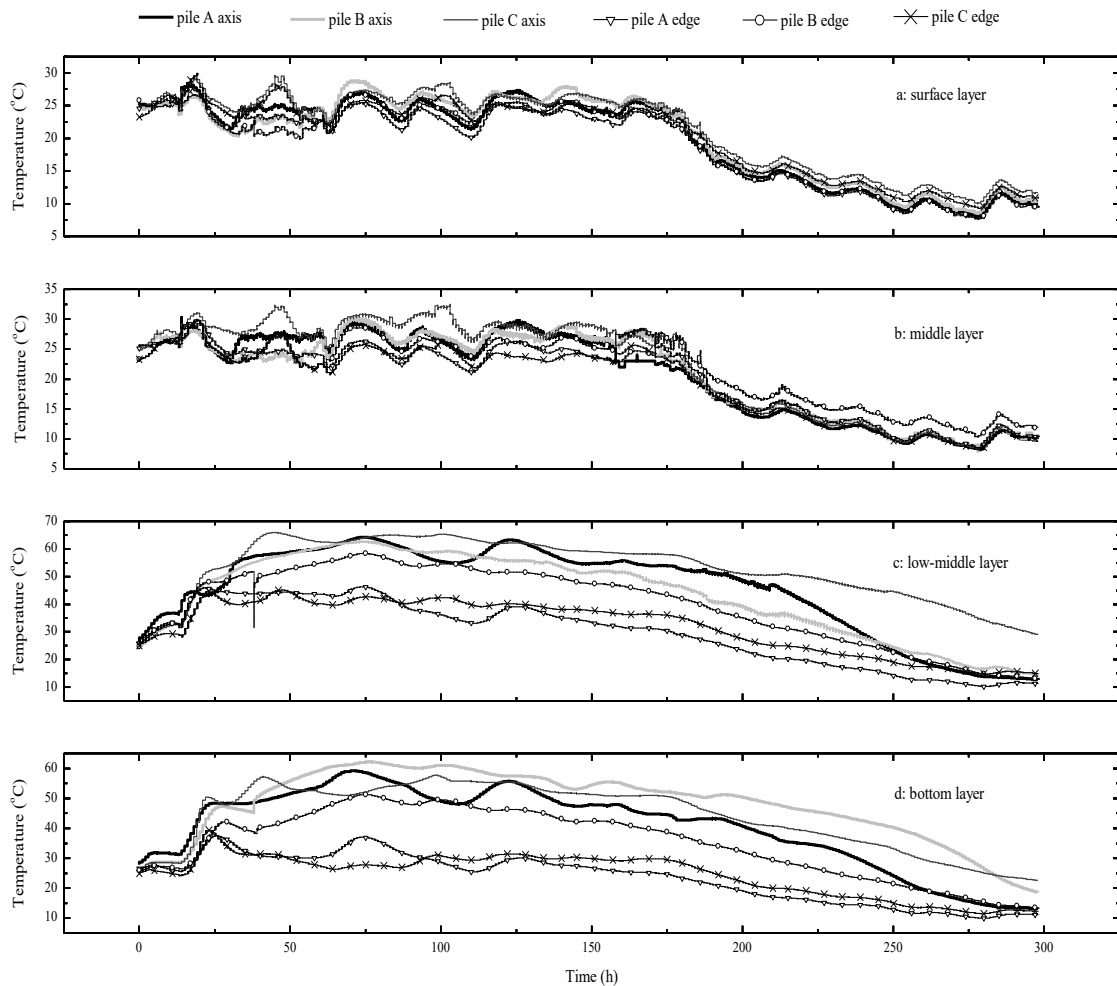

Fig. 2: Changes of temperature in vertical and horizontal gradient in the piles.

Table 5: The highest temperature and the duration of temperature above 50 °C in a horizontal and vertical gradient of each pile.

Horizontal gradient	Vertical gradient	Pile A	Pile B	Pile C
axis	Surface layer	$\dfrac{0}{28.4}$	$\dfrac{0}{28.8}$	$\dfrac{0}{29.6}$
	Middle layer	$\dfrac{0}{30.3}$	$\dfrac{0}{30.3}$	$\dfrac{0}{32.5}$
	Low-middle layer	$\dfrac{148}{64.2}$	$\dfrac{138}{62.7}$	$\dfrac{158}{65.9}$
	Bottom layer	$\dfrac{92}{59.2}$	$\dfrac{164}{62.2}$	$\dfrac{156}{57.8}$
edge	Surface layer	$\dfrac{0}{27.7}$	$\dfrac{0}{26.9}$	$\dfrac{0}{30}$
	Middle layer	$\dfrac{0}{29.5}$	$\dfrac{0}{30}$	$\dfrac{0}{30}$
	Low-middle layer	$\dfrac{0}{46.4}$	$\dfrac{106}{58.3}$	$\dfrac{0}{45.2}$
	Bottom layer	$\dfrac{0}{37.6}$	$\dfrac{13}{51.3}$	$\dfrac{0}{39.4}$

Note: Numerator means the duration of temperature above 50°C (h), denominator means the highest temperature (°C)

cellulose-degrading bacteria, Azotobacter, the absorbent such as clay and zeolite, and metallic salt such as calcium salt and magnesium salts, could be used to reduce nitrogen loss during the composting.

Changes in H_2S Concentration

A similar H_2S emission profile was found in the three piles (Fig. 5). H_2S emissions were first discovered 10 h after the commencement of composting and quickly rose to 45 ppm at 18 h for Pile A, 63 ppm at 15 h for Pile B, and 63ppm at 20 ho for Pile C. The H_2S emission decreased quickly afterward and approached zero after 80h in the three piles. Within this, the H_2S emission in the three piles decreased fast and reached zero after 80 h As a result, H_2S emissions were concentrated between 10 and 20 h following the start of composting, with the highest levels of H_2S emissions occurring between 15 and 20 h. The findings showed that controlling H_2S emissions before 80 h was critical for odor reduction. Li et al. (2008) reported that H_2S maintained a high level in the first 4 days, especially after 1 and 2 days of the experiment.

The results of the H_2S emission showed no significant difference between Piles A and B ($P = 0.402$), and between Piles B and C ($P=0.086$). However, a significant difference was observed between Piles A and C ($P=0.042$). The results also suggest a good correlation between H_2S production and the amount of SS in three piles. The H_2S emissions increased as the sludge content increased in the three piles.

Changes in pH and EC Values

The pH and EC values are presented in Table 6. Overall, the final pH values of compost products of the three piles were higher than the initial pH values, which might be due to the ammonization of organic nitrogen by microbes. The pH values in the surface and middle layers were higher than those in the bottom layer. The difference in pH value in different layers might be caused by the volatilization of ammonium in the nitrification process. The pH values of compost products met the allowed range of 6.5-8.5 for land use（GB8172-87 1987）.
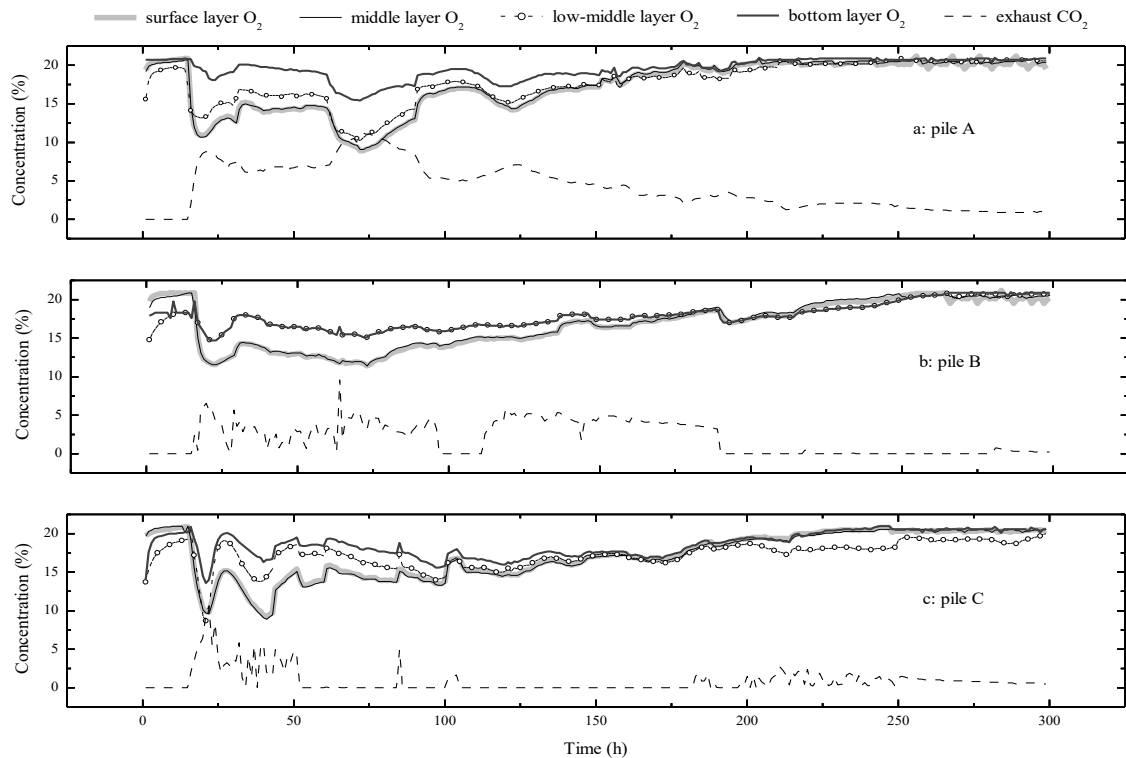
Fig. 3: Changes in oxygen and carbon dioxide concentrations.

The changes in EC values indicated the possible phyto-toxicity or phyto-inhibitory effects (Zhang & He 2006). As shown in Table 6, the compost products at the middle and bottom layers recorded higher EC values than other layers. At the middle and bottom layers, microorganisms were more intensely activated so that more biodegradable organics were decomposed into inorganic salt, which might explain the difference in different layers. The EC values of the compost samples in this study were notably within the Greek standard (e.g., the upper limit is 4.0 mS.cm^{-1}) (Lasaridi et al. 2006). Therefore, the compost products were possibly suitable for land application with proper usage provisions.

Changes in Heavy Metal Concentrations

The heavy metals contents are inclined to increase in the compost product; thus, evaluation of heavy metal content is essential. Table 7 shows the control standards about heavy metals (GB4284-84 1984，CJ/T 309-2009 2009). The contents of heavy metals As, Cd, Cr, Cu, Ni, Pb, and Zn in the end products are listed in Table 8. The heavy metals Zn and Cu exceeded the limits in GB4284-84 （1984), but they were within the B grade standard in CJ/T 309-2009 (2009). Other heavy metal contents in the end products were under the A grade standard in CJ/T 309-2009 (2009). However, metal accumulation should be given sufficient attention

when the compost products are repeatedly applied to the soil (Ko et al. 2008).

Changes in Other Chemical and Maturity Parameters

The chemical and maturity parameters before and after composting are shown in Table 9. The C/N ratio of the composting raw materials was approximately 6-8, which declined to 3-5 in the end products (Table 9). Generally, a final C/N ratio of 20 or below indicates the maturity of the compost with an initial C/N ratio of 25-30. However, the C/N ratio observed in this study did not sufficiently indicate the maturity of the compost because the initial C/N ratio (6 - 8) was not in the range of the initial C/N ratio in the general rule. Another maturity parameter $T = (C/N)_{final}/(C/N)_{initial}$ was proposed by Morel et al. (1985), and compost products were considered as mature when the parameter $T \leq 0.6$. Similarly, Sun et al. (2012b) stated that the compost became mature when T was approximately 0.7. In the present study, T was approximately 0.63, 0.51, and 0.57 in Piles A, B, and C, respectively. Therefore, the compost products reached complete maturity. The compost of Pile B was more mature than that of Piles A and C.

The GI can assess the toxicity and maturity level of compost products. A GI of 50% was used to indicate that the

Table 6: Changes of pH and EC during composting.

	pH			EC[mS.cm^{-1}]		
	Pile A	Pile B	Pile C	Pile A	Pile B	Pile C
Raw material	7.91	7.53	8.21	1.69	1.15	1.71
Product surface layer	8.21	8.44	8.47	1.37	1.34	1.23
Product middle layer	8.3	8.17	8.2	2.44	2.41	2.56
Product bottom layer	8.17	8.23	8.03	2.43	2.46	2.45

Table 7: Control standards for heavy metal content for agricultural use [mg.kg^{-1}].

Control standards		As	Cd	Cr	Cu	Ni	Pb	Zn
GB4284-84	pH＜6.5	75	5	600	250	100	300	500
	pH≥6.5	75	20	1000	500	200	1000	1000
CJ/T309-2009	A Grade	30	3	500	500	100	300	1500
	B Grade	75	15	1000	1500	200	1000	3000

compost was phytotoxin-free（Wong et al. 2001). The GI values of end products in three piles increased significantly and reached 47.5%-70.1%. Therefore, the compost in Piles A and B were sufficiently stable at 300 h.

The MC of compost significantly decreased in the three piles. The MC of end products in piles A and B was within the acceptable limit of 20-35%（CJJT52-93 1993). The largest decrease in MC was found in Pile B, which was 36.7%.

The VS decreased during the composting process for all the piles. Similar results were observed in Wong (2001) and Zhou et al. (2014). Among the three piles, Pile B with a 5:1:1mixture ratio had the highest loss of VS content (14.37%).

CONCLUSION

The co-composting of SS with leaves and rice straw was realized at the mixture ratios of 4:1:1 (Pile A), 5:1:1 (Pile B), and 6:1:1 (Pile C). A ratio of 5:1:1 was found to be the optimum ratio for maintaining the highest temperature. A significant negative correlation was observed between CO_2 and O_2 concentrations. The O_2 utilization in Pile B was higher than that in other piles. The NH_3 and H_2S emissions significantly increased as the ratio of sludge increased. Therefore, special attention should be given to controlling NH_3 pollution caused by composts with a high sludge ratio. Higher EC values were observed in the middle and bottom layers than the top layers in the composting products, but
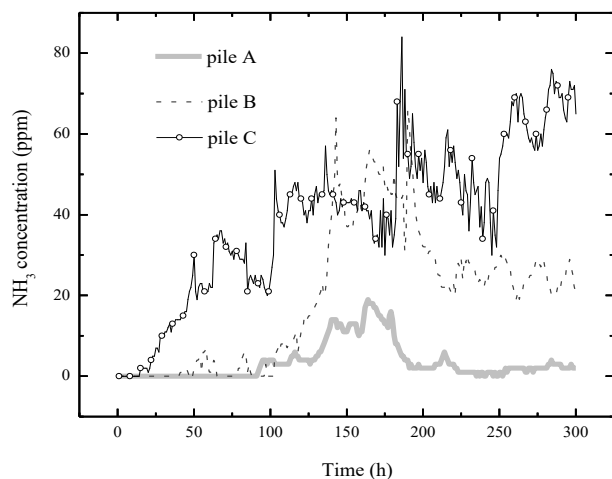

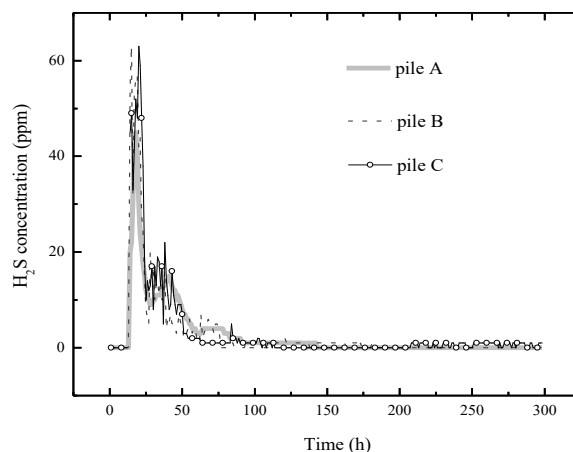Fig. 4: Changes in ammonia concentrations during the composting.

Fig. 5: Changes in hydrogen sulfide concentrations during the composting.

Table 8:Changes in the amount of heavy metals before and after composting [mg.kg⁻¹].

Piles	Time(h)	As	Cd	Cr	Cu	Ni	Pb	Zn
Pile A	0	15.8	0.7	85.8	560.2	45.2	22.5	472.5
	300	15.2	0.9	102.7	653.4	47.5	27.4	523.7
Pile B	0	16.2	0.5	91.0	584.7	43.7	25.6	511.4
	300	18.4	0.8	112.5	705.3	47.8	21.9	463.2
Pile C	0	17.5	0.7	110.4	642.5	55.4	24.3	526.1
	300	20.1	1.1	93.6	589.6	44.6	22.7	447.3

Table 9: The changes of other chemical and maturity parameters before and after composting.

Parameter	Time [h]	Pile A	Pile B	Pile C
C/N	0	7.67	7.31	5.94
	300	4.86	3.73	3.38
GI [%]	0	33.5	30.2	25.4
	300	70.1	70.0	47.5
MC [%]	0	63.8	69.5	73.1
	300	28.7	32.8	41.7
VS [%]	0	82.2	81.17	80.2
	300	70.9	66.8	74.3

they did not exceed the tolerance level for plants of medium sensitivity according to the Greek standard. The pH values in the surface and middle layer were higher than those in the bottom layer, and the pH of the composting products was within the accepted range of 6.5-8.5 for land use. While the Cu and Zn concentrations were within the grade B standard, other heavy metal contents in all the compost products were shown to meet the grade A standard in CJ/T 309-2009 (2009). According to the C/N ratio, GI, MC, and VS, Pile B with a 5:1:1 mixing ratio were more mature than Piles A and C.

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