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Composting of Sewage Sludge with a Simple Aeration Method and its Utilization as a Soil Fertilizer

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Abstract The objective of this study was to examine the feasibility of sewage sludge composting using a simple aeration method. Two consecutive composting trials (run A and run B) using Japanese sludge and woodchips (1:1, v/v) were conducted in cubic boxes ($0.45 \times 0.45 \times 0.45$ m^3) made by plywood at Okayama University. Air was forced up through small holes perforated on two open-ended parallel PVC pipes (ø 16 mm, 0.25 m apart) laid at the base. The results show that compost temperatures were rapidly increased to the peak points of 47.4 °C (run A) and 74.8 °C (run B) within the first 2–3 days and varied depending on each composting run and vertical locations. The changes in physicochemical properties with particular attention to inorganic nitrogen (NH_4–N, NO_3–N) and free amino acid nitrogen (FAA-N) indicated that the biodegradation took place by different mineralization pathways during the composting process. The degradation of organic matter into amino acids followed by ammonification was predominant in run B, whereas the nitrification was greater in run A. A pot experiment using the two finished composts and their raw materials was carried out to study their effectiveness as fertilizer to Komatsuna (*Brassica rapa* var. *perviridis*). The total plant biomass produced by the composts was similar to chemical fertilizer. The lowering proportions of FAA-N/T-N, NH_4–N/NO_3–N, and C/N ratios in the composts compared to those in raw materials was found to correlate with the increase in plant biomass.

Keywords Amino acid · Biodegradation · Composting · Nitrogen · Sewage sludge

Introduction

The disposal of sewage sludge into landfills has been causing serious environmental pollution. In Vietnam, wastewater treatment plants (WWTPs) were estimated to generate approximately 1.2 million dry Mg of sewage sludge annually (Karius 2011). These numbers are predicted to increase continuously in the coming years due to rapid urbanization and development of sewage networks. At present, the popular method for handling of sewage sludge from WWTPs in Vietnam is dumping at sanitary landfills without recovery of the recyclable materials in spite of the increasing awareness of its environmental pollution. In contrast, Japan, before the great east earthquake, generated more than 2.2 million dry Mg of sewage sludge. Remarkably, nearly 80% of sewage sludge is reused and recycled as construction materials, compost, fuel, etc. (MLIT 2011).

Composting of organic waste has long been considered an attractive sludge management option for effective reduction of its volume. Aerobic composting could be performed in small to large scales, i.e., in laboratory (Malińska et al. 2014), pilot (Lu et al. 2008), and industrial composting facilities (Kuter et al. 1985) depending on the purpose of producers. Composted sludge can be used as a soil amendment to supply nutrients to plants, improve soil physical properties, and increase the percentage of organic

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matter (Warman and Termeer 2005; Pedra et al. 2007; Alvarenga et al. 2015), although negative effects associated with heavy metal accumulation and phytotoxicity phenomena in plant–soil systems should be taken into consideration.

Sludge composting is widely applied in developed countries, which emphasize large-scale and mechanized composting process. However, in Vietnam and other developing countries, such processes may face operational costs and other problems regarding the low-quality final product. This is likely due to an incomplete composting process caused by inadequate control temperature, moisture, aeration, or a combination of the above factors. Hence a simple and cost-effective composting method for recycling of sludge and producing commercial compost is necessary to ensure its applicability in developing countries.

Several studies on composting have focused on the changes in compost physicochemical properties (Brewer and Sullivan 2003; El Fels et al. 2014) followed by a seed germination test or plant growth bioassays (Said-Pullicino et al. 2007; Eklind et al. 2014) as indicators of compost stability and maturity. Some have attempted to relate compost measures of stability and maturity to plant growth and N uptake (Cooperband et al. 2003), but information on the active fractions of organic nitrogen like amino acids and amino sugars during composting process is very scarce. Free amino acids are thought to be an easily decomposable organic N and become an important N source for plants (Jones and Kielland 2002), but also the factor limiting N availability for plant uptake due to N source for heterotrophic microorganisms in the soil system.

Therefore, the main objectives of this study are two-fold: first, to examine the feasibility of sewage sludge composting using a simple aeration method, providing information about the changes in physicochemical properties of sludge during the composting process with particular attention to the temperature and the nitrogen availability; and second, to relate some compost properties to plant biomass as a means to evaluate the quality of the self-making composts.

Run A began on 15 February 2016 (winter) and run B began on 19 May 2016 (summer).

Materials and Methods

Sewage sludge and bulking material

In 2016, Japanese sludge samples were collected from the same Green Yuki composting plant located in Okayama prefecture. Due to the seasonal fluctuations in sludge chemical composition (Table 1), two types of sludge were used for the experiment, one was sludge A which was collected in the winter and the other was sludge B which was collected in the summer. Sludges were then transported to the experimental site just before each run of the composting trials. In the preliminary survey, a Vietnamese sludge (V-sludge) sample was collected from a WWTP in Ho Chi Minh City and carried to Japan for laboratory analysis. However, this sludge was not used in subsequent composting experiments due to the feedstock limitation. The physicochemical characteristics of the sludges are presented in Table 1.

Woodchips of Japanese cedar *(Cryptomeria japonica)* with 5–7 cm length were used as the bulking agent to improve aerobic condition during composting. Sewage sludges were mixed with woodchips at a volumetric ratio of 1:1 (36 kg of sludge: 5 kg of woodchips, wet basis).

Composting Facilities

Two aerated composting trials in sequence, run A using sludge A and run B using sludge B, were performed in small scale at Okayama University, Okayama prefecture, Japan. Run A began on 15 February 2016 (winter) and run B began on 19 May 2016 (summer). Composting was monitored for 63 and 57 days for run A and run B, respectively. Two plywood compost boxes ($0.45 \times 0.45 \times 0.45\ \mathrm{m}^3$) were covered by a 50-mm thick styrofoam insulator to reduce heat loss. Air was forced up through small holes perforated on two open-ended parallel PVC pipes (ø 16 mm, 0.25 m apart) laid at the base. The pipes were covered by woodchips to prevent blockage of the holes, and connected to an air pump with a 40-L min^{-1} capacity. For run A, because of the low ambient temperature in the winter, the inlet air temperature was maintained in the range of 20–35 °C by a resistance wire surrounding a 2-m long aluminum pipe connected to a temperature controller. For run B, the air was intermittently supplied with a preset cycle of 1 min aeration and 59 min pause using an automatic time-delay relay. A schematic diagram of the composting system is presented in Fig. 1.

Temperature recording

The temperature within the compost piles was continuously recorded every 5 min by thermocouples which were horizontally placed at the top (0.40 m from the base), middle (0.25 m from the base), and bottom (0.15 m from the base) of the composting boxes. Another thermocouple was placed outside to measure the ambient temperature. All temperature data were averaged to get mean daily values. Some data on day 17 and from day 55 to 63 in run A were not available due to the failure of the data logger.

Table 1 Physicochemical properties of materials used in the experiment

Parameters	Sludge A	Sludge B	V-sludge	Soil
Moisture content (%, d.b.)	473.4 (22.7)	337.7 (17.7)	178.2 (16.7)	8.8 (1.2)
pH (1:5, w/v)	7.5 (0.03)	7.3 (0.06)	6.9 (0.3)	7.3 (0.9)
Volatile solids (%)	77.6 (0.4)	82.0 (0.2)	66.6 (4.0)	–
T-C (g kg^{-1})	379.2 (3.4)	447.4 (20.1)	169.3 (0.7)	nd
T-N (g kg^{-1})	58.7 (4.0)	48.9 (2.2)	22.4 (0.1)	0.2 (0.01)
C/*N* ratio	6.5	9.2	7.6	–
Amino acid-N (g kg^{-1})	1.45 (0.08)	2.53 (0.35)	–	–
NH_4-N (g kg^{-1})	2.39 (0.15)	3.57 (0.41)	4.24 (1.20)	<0.01
NO_3-N (g kg^{-1})	0.02 (0.01)	0.01 (0.003)	3.79 (0.62)	<0.01
T-P (g kg^{-1})	14.3 (0.13)	10.8 (1.25)	7.6 (0.3)	0.1 (0.1)
Troug-P (g kg^{-1})	0.9 (0.07)	1.7 (0.17)	0.4 (0.03)	–
C/P ratio	26.5	41.4	22.3	
Total cations (g kg^{-1})				
K	3.9 (0.1)	4.1 (0.1)	–	2.3 (0.1)
Ca	1.2 (0.1)	2.8 (0.1)	–	1.3 (0.2)
Mg	1.9 (0.1)	1.6 (0.5)	–	1.1 (0.02)
Total heavy metal (mg kg^{-1})				
Zn	757.2 (14.2)	973.8 (8.9)	209.6 (34.5)	–
Cu	380.5 (7.4)	226.2 (1.4)	45.7 (3.1)	–
Mn	185.0 (2.9)	152.5 (1.2)	372.1 (22.1)	–
Pb	3.5 (4.7)	41.0 (2.6)	nd	–
Cd	nd	1.7 (0.1)	nd	–

Values in parentheses are standard deviation ($n = 3$)

nd not detected

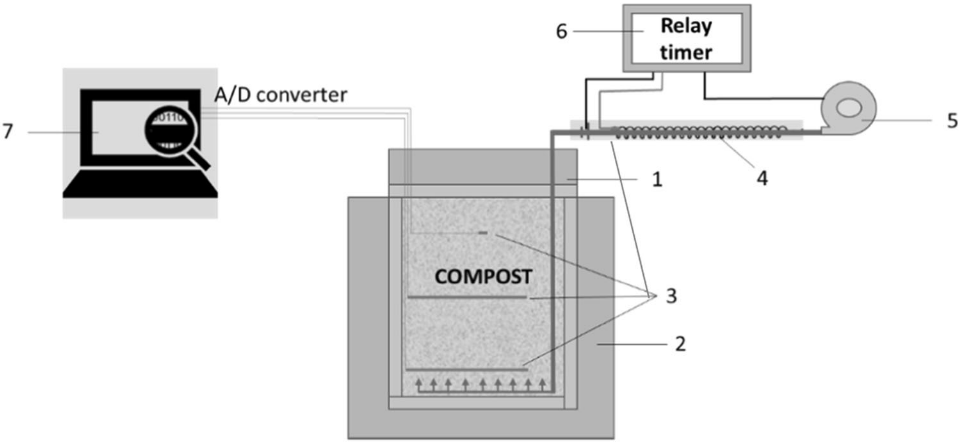

Fig. 1 Schematic diagram of the composting system. 1- box lid, 2- styrofoam insulator, 3- thermocouples, 4- heating system (run A only), 5- air pump, 6- time-delay relay, 7- PC notebook & data logger

Sampling procedures

Compost mixtures were turned and samples were taken on days 0, 11, 28, 46, and 63 for run A, and days 0, 4, 11, 21, 32, 46, and 56 for run B. At each sampling period, triplicate composite samples (about 100 g each, excluding woodchips) were collected at five symmetrical locations from each run and brought back to the laboratory for analysis.

The compost samples were analyzed for pH, NH_4–N, NO_3–N, and free amino acid nitrogen (FAA-N) in fresh condition. The remaining mixtures were then immediately shifted back to each box for continuous composting. Dried samples were then ground to a very fine powder for other measurements, i.e., total carbon, total nitrogen, total phosphorus, and heavy metals.

Pot Culture Experiment

In Oct 2016, a pot culture experiment using the two finished composts (called compost A and compost B from run A and run B, respectively) and aforementioned sludges was conducted in a greenhouse at Okayama University to study the effectiveness as soil fertilizer to Japanese Komatsuna (*Brassica rapa* var. *perviridis*). Soil (3.02 kg, d.b.) was passed through a 2-mm sieve and put into a Wagner pot (surface area: 200 cm^2, height: 20 cm) for all treatments. For amended treatments, either sludges or composts or chemical inorganic fertilizer $(NH_4)_2SO_4$ was applied at a rate of 600 mg N pot^{-1} at the top 0−5 cm layer, which is equivalent to 300 kg N ha^{-1}. After calculating the total P and K contents contributed by sludge or compost, all treatments except the control (soil only) were supplemented with P as super phosphate and K as potassium chloride to get the same rates of 450 mg P pot^{-1} and 300 mg K pot^{-1}, respectively. Komatsuna was cultivated at a density of 12 plants pot^{-1} (the germination ratio of the seeds was above 90%, data not shown). After 41 days of cultivation, all plant parts (leaf and root) were separately harvested and dried at 105 °C for 26 h. Plant biomass was expressed per unit of the dry weight (g pot^{-1}). All treatments were arranged in a randomized complete block design with three replications.

Sample Analysis

The sludges and composts were analyzed for the following parameters: moisture content (105 °C for 24 h); pH (1:5 of fresh sample: water, w/v) using pH electrode; total carbon (T-C) and total nitrogen (T-N) were measured by C-N analyzer (CORDER MT-700; Yanaco, Japan); volatile solid was determined by loss on ignition (550 °C for 3 h); loss of organic matter (OM) and loss of T-N were computed using the equations of Paredes et al. (2000).

$$\text{OM loss}\,(\%) = 100 - 100[X_1(100 - X_2)] \div [X_2(100 - X_1)]$$
$$\text{T} - \text{N}\,(\%) = 100 - 100\,[(X_1 N_2) \div (X_2 N_1)]$$

where X_1 and X_2 represent the initial ash content and the ash contents at a time *t*, respectively; N_1 and N_2 represent the initial nitrogen content and the nitrogen contents at a time *t*, respectively. FAA-N was extracted by shaking 5 g of fresh sample with 50 mL of deionized water, followed by centrifugation at $8256 \times g$ (10,000 rpm for 5 min) and storage of supernatant solution at −30 °C to await analysis. The analytical procedure followed that of Chantigny et al. (2007). Briefly, 2 mL of dissolved organic matter sample and 1.25 mL of ninhydrin reagent were added in sequence to test tubes. The tubes were capped, shaken and kept in the water bath at 95 °C for 25 min. After cooling, 4.5 mL of ethanol (50% v/v) were added to the tubes and absorbance read at 570 nm on the spectrophotometer (UV-1200, Shimadzu, Japan). A standard curve was prepared from six different concentrations of L-Leucine-N (from 1 to 16 mg N L^{-1}) and the results were expressed in terms of L-Leucine-N equivalents. Inorganic nitrogen was extracted by 2 N KCl; NH_4–N was measured by salicylate-hypochlorite method (Tan 1996) and NO_3–N was measured by vanadium(III) chloride reduction method (Doane and Horwath 2003). Organic-N was calculated as the difference between T-N and inorganic N (sum of NH_4–N and NO_3–N). Total-P (T-P) and available P (Troug-P) were determined by molybdenum blue method; total cations (K, Ca, and Mg) and total heavy metals (Zn, Cu, Mn, Pd, and Cd) were determined using atomic absorption spectrometry (AA-6800, Shimadzu, Japan) after dry ashing samples and dissolving in 10 mL 50% v/v HCl (Faithfull 2002).

Statistical Tests

The mean values of total plant biomass in the pot culture experiment were compared according to Fisher's protected least significant difference test at $P < 0.05$ using EXCEL ® macro add-ins DAAASTAT version 1.512 (Onofri and Pannacci 2014).

Results

Composting temperature

Compost temperature is a very important parameter indicating the success or failure of a composting process. The ambient temperatures ranged from 4.3 to 18.2 °C in run A and from 25.0 to 33.4 °C in run B (Fig. 2). In run A, the temperatures immediately increased after composting and reached 47.4, 39.1, and 32.7 °C on day 2 in the top, middle and bottom locations, respectively. In run B, peak temperatures occurred later on day 3 and reached higher values of 43.8, 74.8, and 55.7 °C in the top, middle and bottom locations, respectively. After peaking, the temperature gradually cooled down and somewhat returned to the ambient temperature. At some locations, i.e., run A-bottom or run B-middle, compost temperatures were found to increase again. At the end of the process, the compost temperatures ranged from 9.4 to 19.1 °C in run A and from 19.7 to 55.3 °C in run B (Fig. 2).

Moisture Content

It is noted that our moisture data are expressed on a dry weight basis which emphasizes the changes of mass of water compared to their initial dry mass of solids. The sludge used in these experiments had high moisture contents (473.4% in sludge A, and 337.7% in sludge B). During composting, the moisture contents gradually decreased to 118.8% in run A and 74.0% in run B as a consequence of common evaporation of water. Despite having a higher initial moisture content, the loss of moisture in run A was greater than run B (Table 2).

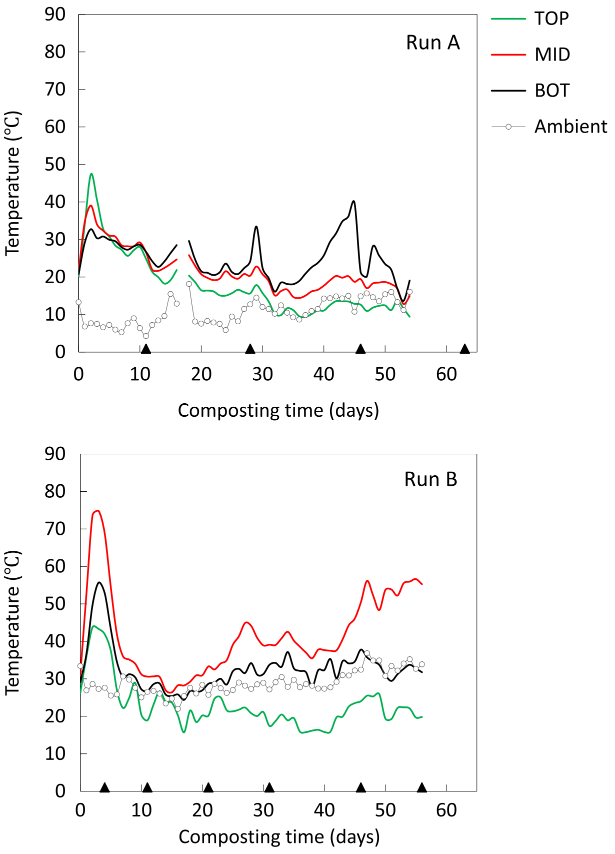

Fig. 2 Temperature profiles at the top, middle and bottom of the composts for; **a** run A, and **b** run B. Black triangles (▲) on the *x*-axis indicate times for turning/sampling events

pH

The composts had an initial pH value of 7.5 (run A) and 6.6 (run B), which rapidly increased to maximum values of 8.6 for run A and 9.0 for run B within 4–11 days. After that, the pH gradually decreased until the end of the composting process. The difference in the pH values between two finished composts was about 1-unit pH (5.7 in compost A and 6.8 in compost B). Both sludges were expected to be compatible with Komatsuna plant in the pot experiment.

Total Volatile Solids, OM and T-N Loss

Total volatile solids, OM, and T-N loss indicated the degradation of organic matter. The total volatile solids substantially decreased from 75.2 to 69.2% in run A and from 83.9 to 69.2% in run B. Most of T-N losses occurred during the first 11 days, while OM loss extended longer in later periods as found in run B. At the end of composting, the percent of OM losses were 25.7% and 50.2% in run A and run B, respectively. Similarly, after composting, T-N losses were 32.8% in run A and 44.4% in run B (Table 2).

Total Carbon, Total Nitrogen, and C/N Ratio

Microorganisms use carbon as a source of energy and nitrogen for their population growth. In both sludges T-C and T-N changed as a result of OM and T-N losses during composting. The T-C decreased from initial values of 380.8–329.3 g kg^{-1} in run A, and from 414.2 to 331.7 g kg^{-1} in run B at the end of the process (Table 2). Similarly, T-N decreased from 60.8 to 50.6 g kg^{-1} in run A and from 51.6 to

Table 2 Changes in physicochemical properties during composting

Composting time (days)	Moisture content (%, d.b.)	pH	Volatile solids (%)	OM loss (%)	T-N loss (%)	T-C (g kg^{-1})	T-N (g kg^{-1})	C/N ratio	NH_4/NO_3 ratio
Run A									
0	470.8	7.5	75.2	0.0	0.0	380.8	60.8	6.3	254.3
11	331.1	8.5	70.2	22.0	30.9	347.2	50.3	6.9	179.8
28	265.2	6.8	–	–	–	–	–	–	6.4
46	175.6	6.3	69.5	24.5	30.4	337.4	52.1	6.5	1.6
63	118.8	5.7	69.2	25.7	32.8	329.3	50.6	6.5	1.0
Run B									
0	299.9	6.6	83.8	0.0	0.0	414.2	51.6	8.0	923.3
4	249.6	9.0	76.9	26.3	34.6	384.7	40.7	9.5	1239.2
11	203.1	8.9	77.2	25.1	42.9	381.7	35.2	10.8	1390.6
21	222.2	8.5	77.7	23.1	38.7	362.1	37.0	9.8	4602.1
32	168.5	7.5	72.8	40.7	39.1	350.0	44.7	7.8	282.5
46	102.0	6.7	70.0	48.3	44.0	335.2	45.3	7.4	13.8
56	74.0	6.8	69.2	50.2	44.4	331.7	46.2	7.2	8.1

46.2 g kg^{-1} in run B (Table 2 and Fig. 4). Consequently, *C*/*N* ratios of the finished composts, which were 6.5 in run A and 7.2 in run B, showed little change during the whole process. Nevertheless, the slight increase in *C*/*N* ratio from 8.0 to 10.8 found in run B during the first 11 days indicated that the loss of nitrogen exceeded the loss of carbon during the same period of time.

Inorganic N

The initial NH_4–N contents in run A and run B were 3.63 and 10.73 g kg^{-1}, respectively. For run A, the NH_4–N content increased dramatically to 18.9 g kg^{-1} by day 11, thereafter, dropped to 6.2 g kg^{-1} by day 28 and fluctuated between 7.8 and 8.7 g kg^{-1} from day 46 to day 63. For run B, the NH_4–N also increased rapidly to 24.3 g kg^{-1} by day 4, but then gradually decreased to 5.8 g kg^{-1} at the end of process (Fig. 3). In contrast to the trend of changes in NH_4-N, NO_3-N contents showed a gradual increase in the latter stages when temperatures have been reduced to ambient levels. It should be noted that the increase of NO_3–N in run A was much greater than run B. As a result, the final amounts of NO_3–N were also clearly different in the two runs. By the end of the process, the NO_3–N concentration in compost A was 13 times higher than compost B (Fig. 3). In addition, the NH_4–N/NO_3–N ranged from 254.3 to 1.0 in run A and from 923.3 to 8.1 in run B (Table 2).

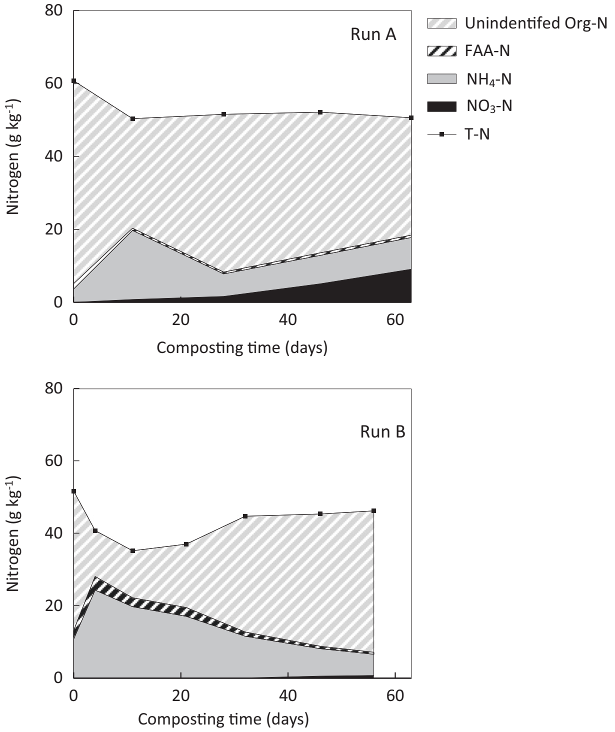

Fig. 3 Changes in nitrogen forms during composting process. Areas of diagonal stripes indicate values of total organic nitrogen. Data are means of replicates ($n = 6$ for run A and $n = 2$ for run B)

Amino Acid-N

Amino acids are nitrogen-containing organic compounds that contribute significantly to organic matter. In this study, the changes in FAA-N were measured to assess biodegradation during the composting process. In run A, the amount of FAA-N markedly decreased from an initial value of 1.45 to 0.61 g kg^{-1} during the first 11 days, and then maintained a steady level until the end of composting. In run B, the amount of FAA-N was found to increase sharply during the first 4 days, from 2.43 to 3.77 g kg^{-1}, then gradually decreased until the end of the composting process. The finished composts had the FAA-N contents in the range of 0.57–0.65 g kg^{-1} (Table 1; Fig. 3).

In short, except for NO_3–N, most of the physicochemical changes occurred during the first 30 days of composting. During this period, the results indicated that the degradation of organic matter into amino acids and the transformation from amino acids to NH_4–N via synthesis—ammonification were predominant in compost run B, whereas, the nitrification in run A was found to be more intense after day 30.

Pot Culture Experiment

The pot culture experiment was employed to assess the overall quality of finished composts and determine the presence of phytotoxins. Total biomass as the sum of leaf and root dry weight was found to be significantly affected by sludges and finished composts (Fig. 4). Pots receiving sludge A, compost A, and compost B produced the same total biomass (mostly as leaf biomass) as those receiving

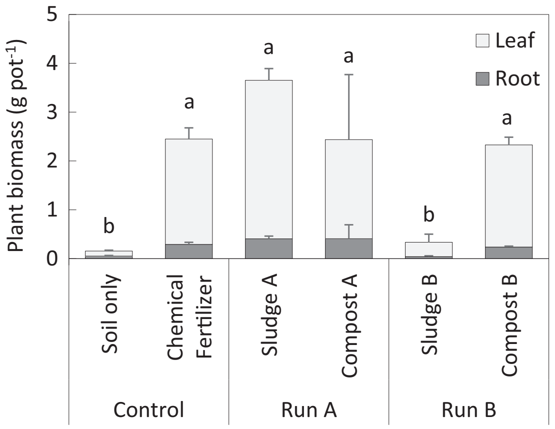

Fig. 4 Plant biomass as effected by composts and their sludges. Bars represent standard deviation of the mean ($n = 3$). Different letters indicate significant differences among treatments ($P < 0.05$)

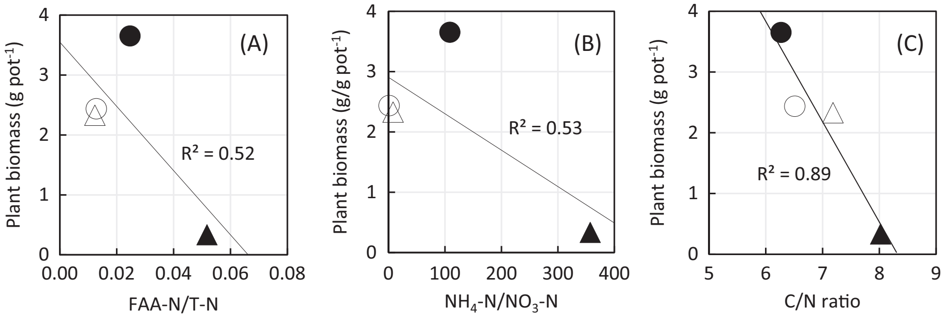

Fig. 5 Relationship between FAA-N/T-N, NH4-N/NO3-N, C/N ratio of amendments and total plant biomass. Data are means of 3 replicates. (● = Sludge A; ○ = Compost A; ▲ = Sludge B; △ = Compost B)

chemical fertilizer. In contrast, total biomass produced by sludge B was very low, which was not significantly higher ($P > 0.05$) than that obtained by the control treatment (soil only). The inhibition effects were more clearly when we analyzed the relationship between total biomass and several important variables of sludges and composts. The results show that total biomass was negatively correlated with the compost FAA-N/T-N, NH_4–N/NO_3–N and *C*/*N* ratios ($R^2 = 0.52$, $R^2 = 0.53$, and $R^2 = 0.89$, respectively) (Fig. 5).

Discussion

The results of current study demonstrated that the ambient temperatures affected the changes in physicochemical properties during the composting process. The peak temperatures achieved under low ambient temperature condition were lower than those in the high ambient temperature. The rapid increase in compost temperature in the initial phases of the composting process was associated with decomposition of the organic materials. The temperature increase in later periods could be due to the turning immature materials to desirable locations for consecutive decomposition of organic matter. The continuous introduction of warm air from the bottom was aimed to supply oxygen and prevent heating loss. This air supply directly affected convection heat currents moving upward and caused an atypical distribution of temperature in the compost in run A. In contrast, the intermittent introduction of air in run B possibly produced the usual distribution of "self-heating" caused by microbial activities. The distribution of temperature in run B was consistent with other literature (Tiquia and Tam 2000; Larney and Olson 2006).

The optimum temperature range for composting sewage sludge in a forced aeration system to achieve the maximum rate of biodegradation is between 35 and 55 °C (McKinley and Vestal 1985). However, the compost temperature above 70 °C would result in slower decomposition and nitrogen loss especially at low *C*/*N* ratios (Cofie et al. 2009). Therefore, in order to achieve an acceptable level of pathogen destruction in composting of sewage sludge, maintaining a minimum temperature of 55 °C for at least three consecutive days is necessary (Burge et al. 1978). Except for a short temperature rise in the middle–bottom portions of run B, both runs would not meet above criteria because of possible heat losses to the surroundings due to the insufficient insulation of the compost boxes, especially under low air temperature condition as seen in run A. Wang et al. (2013) used mathematical models to study the feasibility of sewage sludge composting in cold climate environments. Their results indicated that low ambient temperatures could be one of the reasons of heat losses that increased the heat transfer rate to the surroundings and it was difficult to maintain a desirable period of thermophilic condition. The heat loss would also occur when the compost is being turned frequently preventing the compost temperatures from reaching optimum temperature (Tiquia et al. 1998).

Moisture content was documented to be more influential for microbial activity than temperature (Liang et al. 2003). A moisture content of 60–70% wet base (150–233% dry base) provided maximum microbial activities. Another reason for not achieving the temperature above 55 °C in run A could be the higher initial moisture contents in its raw material, suggesting the requirement for drying of sludge to achieve to initial optimum moisture content. In aerobic conditions, the increase in pH at the beginning of the process is the result of degradation of proteins, amino acids and peptides that release ammonium or volatile ammonia (Said-Pullicino et al. 2007; Gigliotti et al. 2012). The drop in pH over time is a consequence of activity of acid-forming bacteria that break down complex compounds into organic acids in the finished product (Diaz et al. 2007).

In spite of the fact that OM loss and T-N loss in run B were much higher than run A, the results of T-N losses measured during the composting of sewage sludge in the current study were consistent with those reported by Witter and Lopez-Real (1987). This could be explained by sludge B may have contained more FAA-N than sludge A, resulting in this difference (Table 1). Although two sludges originated from the same WWTP, they had different organic fractions depending on the season of the year. In addition, the higher compost temperature achieved in run B also contributed to greater reductions of volatile solids, greater OM and T-N losses (Table 2).

The decline in T-C during aerobic composting was attributed to the mineralization of organic matter resulting in the evolution of CO_2, H_2O, and heat (Garcia et al. 1991; Li et al. 2013). Meanwhile, the decrease in T-N was due to the loss of N as NH_3 as reported by Witter and Lopez-Real (1987). However, an increase in T-N in from day 11 to day 32 as found in run B indicated a great reduction of the total weight and total volume of the compost mass.

The *C*/*N* ratio in solid phase was traditionally used to determine the degree of maturity (Iglesias Jiménez and Perez Garcia 1989). The optimum range in *C*/*N* ratios from 25 to 35 would be recommended for several types of commercial composts because most bacteria need approximately 30 g of C for 1 g of N uptake (Cofie et al. 2016). However, there is no general agreement regarding which value of the *C*/*N* ratio indicates maturation of sewage sludge compost due to the relative N-richness of the feedstock. Instead of *C*/*N* ratio in solid phase, some authors suggested that the *C*/*N* ratio in water extract could be a better predictor of compost stability (Chanyasak and Kubota 1981; Hue and Liu 1995). Our results show that finished composts had smaller *C*/*N* ratios (6.5–7.2) than the optimum range, but they were not significantly different from other Japanese commercial composts based sewage sludge (data not shown). In this study, woodchips served as a bulking agent during whole composting process. The woodchips properly increased the initial *C*/*N* ratios of the feedstock to achieve better performance for composting. Malińska and Zabochnicka-Świątek (2013) indicated that mixing sewage sludge with woodchips at a ratio of 1:1 (d.b.) allows the optimal initial moisture content of 69% (w.b.), *C*/*N* ratio of 30:1 and air-filled porosity of 52% across the composting pile. Although being recovered at the end of process, the woodchips could not be separated completely from the finished composts. Consequently, they might have contributed to the carbon source of the finished composts.

The increase in NH_4–N with the increase in temperature and pH during the first 4–11 days reflected the degradation of organic matter (Brewer and Sullivan 2003). After an initial increase, NH_4–N contents decreased because of immobilization inorganic N into organic forms as humus-like materials. However, the decline in NH_4–N during the first 30 days was not associated with an increase of NO_3–N as reported by Paré et al. (1998). The continuous introduction of inlet air at a very slow rate in run A might have induced a nitrification process in which NH_4–N was assimilated to produce the NO_3–N form. In run B, the NO_3–N concentration was negligible during the first 21 days because nitrifying bacteria were likely to be inactive due to the excess amount of NH_4–N as an inhibitor (Fang et al. 1999). Thus, the NO_3–N and NO_2–N contents were higher under better aerobic condition (Brouillette et al. 1996) and nitrification hardly occurs under thermophilic conditions (Morisaki et al. 1989). The decrease in NH_4–N combined with the increase in NO_3–N; on the other hand, NH_4–N/NO_3–N decreased over time suggesting that compost has reached maturity (Paré et al. 1998). The optimum values of NH_4–N/NO_3–N ranged from 0.3 to 3.0 suggesting the maturity level of compost, whereas levels of above 3.0 may reveal an immature condition (Brinton 2000, as cited in Cofie et al. 2016).

To our knowledge, no studies regarding to composting of sewage sludge indicated an optimum level of free amino acid-N in the finished compost. This leads us to consider that measuring of this parameter might have potential to assess the compost stability and maturity, although our data presented herein are insufficient to suggest whether FAA-N can be used as a reliable indicator. The overall decrease in FAA-N at the end of the process, as reported above, suggested that it was gradually assimilated by microbes. Thus, the degradation of organic matter that produces amino acids was not counterbalanced by destructive degradation of amino acids with increasing composting time. Baca et al. (1994) indicated the changes in the amino acid composition reflected the changes in the composition of the microbial population. In their study, amino acids were divided into four groups: acidic, basic, neutral, and sulfur. The total acidic amino acids of the four groups decreased by about 36% of the initial value during 90 days of composting. A general decrease in the amounts of free amino acids during humification of organic matter was also reported by Lähdesmäki and Piispanen (1989).

The results from the pot experiments indicated the ability of sludge and compost to supply available nitrogen for plant growth. However, the use of sludge as a soil fertilizer is not recommended due to high moisture content and high risk of phytotoxic effects as seen in sludge B. For example, total plant biomass produced by sludge B was very low, suggesting an inhibition effect of this immature material. It is noted that all treatments were carried out on sandy soil with a low background in buffer capacity and nutrient contents (Table 1); hence, the amended materials could directly affect the plant growth. The transformation of protein to amino acids is considered as the major factor limiting N availability in soil (Jones and Kielland 2002). In another study conducted by Hara et al. (1999), free amino acids were measured using paper chromatography for evaluating degree of swine compost maturity. Their results indicated that the growth inhibition disappeared when the free amino acids decreased and were in equilibria.

The higher amount of FAA-N in the immature sludge B could be one of the causes of the phytotoxicity effect. In that case, the plant could not use available nitrogen sources due to blockage of soil available nitrogen by microbial activities. Padgett and Leonard (1996) indicated that the addition of an individual amino acid (2 mM glutamine, glycine, aspartic acid, or arginine) to the culture medium with 1 mM nitrate completely inhibited NO_3–N uptake. The inhibition effects on growth of Komatsuna were also investigated by Kubota et al. (1983), who demonstrated that the presence of low fatty acids and relatively high values of org-C/org-N ratios in the immature composts resulted in lower plant biomass. In addition, the emission of ammonia from the raw materials having a high concentration of NH_4-N may also contribute to the phytotoxic effect on plant growth as reported by Wong and Chu (1985).

Variation in Sludge Properties and Composting Applicability in Vietnam

Development of composted materials from sewage sludge has been employed by municipal utilities for years. Open type composting systems i.e. windrows or aerated static pile system and container type systems (in-vessel) are regarded as two common methods of composting sewage sludge. Bin composting used for the current study is perhaps the simplest in-vessel method, in which the materials are contained by walls and usually a roof. Although the methods discussed here might not be "on-farm" composting, this simple composting method is thought to be applicable to suburban and urban settings due to some reasons. One of the reasons is that the system allows for containment and treatment of air to remove odors before release. In addition, the relative small amount of land in the city also increase its applicability in these settings over other types of composting (Plett et al. 2000).

As given in Table 1, Vietnamese sludge (V-sludge) had lower moisture content, volatile solids, T-C, T-N, T-P, exchangeable cations, total Zn and Cu but higher NO_3–N and Mn than Japanese sludge, depending on the variation of wastewater sources and wastewater treatment systems. Even though originating from the same WWTP, sludge properties can also fluctuate seasonally. For example, at times of rainstorms, the flow of sewage may be too high to be accommodated by the downstream treatment stages. In that case, the sludge might contain more resistant soil particles like silica, that caused a lower volatile solids and nutrient contents as seen in V-sludge properties. However, such differences are thought not to affect the composting process, because basically, V-sludge contained similar proportions of C:N:P in comparison to Japanese sludge, which are maybe more important than the nutrient concentrations.

In Vietnam, composting is not a common practice due to number of reasons. These include high operation and maintenance cost, inadequate management of composting process that caused poor performance or low-quality compost. This is likely due to an insufficient control of temperature, moisture, aeration or a combination of the above factors. A wide variation in sludge constituents leads to a wide variation in compost quality, however, its utilization of different composts must be adjusted accordingly to ensure beneficial results. Therefore, any study related to compost may expand the state of knowledge for composting of sewage sludge and support advances in practices of municipal utilities in both developed and developing countries.

Conclusions

The composting of sewage sludge with woodchips as a bulking agent is feasible using a simple aeration method in small scale. The compost temperature in run A (winter) was not well controlled in comparison to that in run B (summer). The degradation of organic matter into amino acids followed by ammonification was predominant in run B, whereas the nitrification was greater in run A.

The finished composts had pH values of 5.7–6.8, C/N ratios of 6.5–7.2, T-N of 46.2–50.6 g kg^{-1}, FAA-N/T-N of 1.23–1.28% and NH_4–N/NO_3–N of 1.0–8.1. Although sludge properties varied seasonally, total plant biomass produced by two finished composts was over the control treatment and comparable to commercial chemical fertilizer. Clearly, the lowering of FAA-N/T-N, NH_4–N/NO_3–N, and *C*/*N* ratios in composts compared to those in raw materials was found to correlate with the increase in plant biomass.

Since the replications were not included in separate composting boxes for each compost type within the same condition, it could not be compared the precision of the different composting systems. But this study might provide valuable information on final compost quality which will support for our next composting projects in Vietnam. The tropical climate appears to be more favorable to maintain optimum temperature during composting. However, further research is needed to use the Vietnamese sludge feedstock to be adapted to local conditions.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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