Research Article

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Enhanced water reduction by turning during sewage sludge composting

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Abstract

BACKGROUND: Turning can supply oxygen and increase dewatering efficiency during composting. This study was conducted to investigate the influence of turning on water removal and the interactive influence of turning during different phases. Dewatered sewage sludge was composted using control technology for bio-composting, during which the temperature, free airspace, pile settlement and water reduction were measured and calculated. During the temperature-increasing and thermophilic phase, turning once and without turning were performed and compared. During the cooling phase, higher (every 2 days) and lower (every 4 days) turning frequencies were used and compared.

RESULTS: The results showed that there was a significant difference in water removal between the different turning modes during three phases (*P* value of temperature increasing, thermophilic and cooling phase, respectively, 0.0122, 0.0092 and 0.0056). Furthermore, the water removal was significantly related to the interaction between different turning modes during the thermophilic phase and cooling phase ($P = 0.0092$).

CONCLUSION: No turning in the temperature-increasing phase, turning once in the thermophilic phase, and turning every 4 days in the cooling phase was the most efficient turning strategy for water removal, for which the water reduction was 591.63 kg ton^{-1} matrix, significantly higher than those in other treatments.

Keywords: sludge; environmental biotechnology; waste treatment and waste minimization; engineering

INTRODUCTION

Composting is a principal method for sewage sludge (SS) reduction. Water removal during SS composting is considered to be an effective sludge reduction process that benefits the storage and transportation of SS composting material. A SS composting system is usually a semi-open system with a single direction of ventilation along the blowing direction, and the diversities in heat and mass transfer rate often result in spatial differences of the moisture content, temperature, and volatile solids (VS).[1−3] In static composting, compaction results in pile settlement and lower free airspace (FAS), and this can significantly affect the efficiency of oxygen supply, water evaporation and heat ventilation rates in a composting pile.[4] Although turning increases FAS rapidly and makes the pile loose, it leads to a large heat loss and considerable temperature decrease, which obviously impacts on the drying process. Composting should employ a turning strategy that removes more water during a short period.

Several studies have been conducted on the relationships between turning and the SS characteristics such as material maturity, carbon and nitrogen change, microbial consortia, temperature and heat change.[4−9] However, only a few studies have focused on the relationship between turning and water reduction. Composting can be divided into the temperature-increasing, thermophilic, and cooling phases.[10,11] Although many researchers have used the turning operation in experiments, the turning frequencies in each phase are similar,[12−14] and most of them are conducted by manpower, the practical guidance for a turning machine in plant-scale composting is lacking. To date, no clear technological parameters have been established for the opportunity and frequency of mechanical turning during the composting process, particularly at plant scale.

In this study, different turning modes were designed for each phase. We determined the FAS, pile settlement and temperature change during the whole period for each pile and measured the moisture content and VS content of the initial material and composted product (CP). Based on the calculation of total water removal, the effect of turning frequency in the different phases on water reduction was assessed, and an optimal turning strategy was designed.

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Table 1. Design of the turning strategy in each treatment

	Turning time		
Treatment	Temperature-increasing phase	Thermophilic phase	Cooling phase (No. of days interval)
T1	0	0	4
T2	0	0	2
T3	0	1	4
T4	0	1	2
T5	1	0	4
T6	1	0	2
T7	1	1	4
T8	1	1	2

MATERIALS AND METHODS

Composting materials

This study was performed in the Municipal Sewage Sludge Treatment Plant, Changchun, China, where SS and CP were collected. Corn stalk (CS) was also obtained from the same city. CS was passed through a cutting mill to produce approximately 3 cm pieces of CS. CS and CP were used as bulking agents for composting. SS, CS, and CP were added to three feed bins, and then fed into a mixing machine using screw conveyors. The mixing ratio of the three materials was 3:2:1 (SS: CP: CS by volume). This ratio was selected based on the initial moisture content and the FAS of the composting material that was appropriate for microbial fermentation.[15,16] The values of moisture content of SS, CS and BP were 80.3 $\pm$ 0.49%, 15.6 $\pm$ 0.45% and 44.8 $\pm$ 0.66%, respectively, the values of VS content were 61.3 $\pm$ 0.11%, 96.3 $\pm$ 0.18% and 51.9 $\pm$ 0.39%, respectively.

Experimental procedures

The mixture for composting was loaded into the composting compartment, flattened using a slope trimmer, and then subjected to composting by CTB (Control Technology of Bio-composting) auto-control.[16] The total composting period was 22 days. The size of the composting pile was 34 m $\times$ 5 m $\times$ 1.6 m (L $\times$ W $\times$ H). Air was supplied from the bottom to the top of the pile using air blowers. The aeration parameters were adjusted at different composting stages based on temperature (T). The aeration period was 40 min (aerated for 5 min and unaerated for 35 min) during the temperature-increasing phase ($T < 50^\circ$C), and the airflow rate was 56 m^3 min^{-1} for each pile. During the thermophilic ($T > 50^\circ$C) and cooling (from the end of the thermophilic phase to the end of the composting period) phases, the aeration period was 40 min (aerated for 10 min and unaerated for 30 min) and the airflow rate was 76 m^3 min^{-1} for each pile.

Turning was conducted using a turning machine (Green-Tech Environmental Engineering Ltd, Beijing, China) with a turning depth of 1.5 m.

Considering the different physical and chemical properties, as well as biological reactions in each phase, this study designed different turning modes for each phase. As shown in Table 1, during the temperature-increasing and thermophilic phases, turning once and no turning were employed; during the cooling phase, higher (every 2 days) and lower (every 4 days) turning frequencies were employed.

The turning time in each treatment was according to the experimental design. T1 was turned on days 12, 16, and 20. T2 was turned on days 12, 14, 16, 18, and 20. T3 was turned on days 8, 11, 15, and 19. T4 was turned on days 8, 11, 13, 15, 17, and 19. T5 was turned on days 2, 11, 15, and 19. T6 was turned on days 2, 12, 14, 16, 18, and 20. T7 was turned on days 2, 8, 12, 16, and 20. T8 was turned on days 2, 8, 12, 14, 16, 18, and 20.

Data acquisition and sample analysis

The temperature in each pile was monitored in real time using a CTB temperature sensor (Green-Tech Environmental Engineering Ltd., Beijing, China) throughout the study period. The sensor sampling points were inserted into the pile at depths of 0.2 m, 0.7 m, and 1.3 m from top to bottom (when the pile height was lower than 1.4 m, the depths were 0.2 m, 0.7 m and 1.2 m), each point was based on three replicates. The moisture content of the composting material was measured by drying the sample at 75°C for 24 h, the VS content was determined by incinerating the oven-dried sample in a muffle furnace at 450°C to constant weight. The collected composting material was also used to determine the bulk density by the cutting ring method, which was used to determine the FAS of the pile. The moisture content, VS and bulk density were analyzed using the methods described by the US Department of Agriculture and US Composting Council[17] and were determined based on nine replicates. The weight of each pile was measured by loadometer, the height of each pile was measured based on nine replicates.

Statistical analysis

One-way analysis of variance (ANOVA) was used to compare the different composting treatments. Multiple comparisons between treatments were compared using the Least Significant Difference test (LSD-t). The SPSS 19.0 software for Windows was used for ANOVA and LSD-t test. The DPS 7.05 was used for ANOVA of orthogonal experiment.

Formulae for data computation

Determination of free air space

The FAS distribution function can be estimated using Equation (1):[18]

$$\mathrm{FAS} = 1 - \frac{Y_m \times S_m}{G_m \times Y_w} - \frac{Y_m \times (1 - S_m)}{Y_w} \tag{1}$$

where FAS is the free air space (%); Y_m is the wet basis moisture content (%); S_m is the solid content (%); Y_w is the density of water (1000 kg m^{-3}); $G_m$is the relative density of composting material (nondimensional).

G_m is calculated using:

$$\frac{1}{G_m} = \frac{V_s}{G_v} + \frac{1 - V_s}{G_f} \tag{2}$$

where G_v is the relative density of VS (nondimensional), and is generally 1; G_f is the relative density of ash (nondimensional), and is generally 2.5; V_s is VS content (%).

Determination of water removal

In this study, moisture content is expressed on a wet-weight basis. Assuming that the change in the weight of the pile is determined by the degradation of VS and migration of moisture, and that the ash content of the pile does not change throughout the composting process, the removed water Δm_{H_2O}(kg), including the water in the pile, the water produced during composting $\Delta m_{H_2O,\ VS}$ (kg),[19,20] and the total removed water ΔM_{H_2O}(kg) can be obtained from the following formula:

$$\Delta M_{H_2O} = \Delta m_{H_2O} + \Delta m_{H_2O,\ VS} \tag{3}$$

Δm_{H_2O} in the pile can be obtained from the following formula:

$$\Delta m_{H_2O} = 1000M_0 \times \frac{C_{H_2O0}}{100} - \frac{1000M_0\left(1-\frac{C_{H_2O0}}{100}\right)\left(1-\frac{C_{VS0}}{100}\right)}{\left(1-\frac{C_{H_2Ot}}{100}\right)\left(1-\frac{C_{VSt}}{100}\right)}\cdot\frac{C_{H_2Ot}}{100} \tag{4}$$

where M_0 is the initial weight of a pile (ton). C_{H_2O0} and C_{VS0} are the moisture and VS contents (%) of the composting material on day 1, respectively. C_{H_2Ot} and C_{VSt} are the moisture and the VS contents (%) of the composting material at the end of the period, respectively.

The microbial water production coefficient k of the organic matter is determined in microbial degeneration. Considering the proportion of the main chemical element in the organic matter, which has a chemical formula of $C_{10}H_{19}O_3N$ and $k = 0.7164\ g\ g^{-1}$,[20] $\Delta m_{H_2O,\ VS}$ can be obtained from the following formula:

$$\Delta m_{H_2O,\ VS} = 0.7164 \times \Delta m_{VS} \tag{5}$$

where Δm_{VS} is the quality of the biologically degraded solid on a dry basis, and thus calculated using:

$$\Delta m_{VS} = 1000M_0 \times \left(1-\frac{C_{H_2O0}}{100}\right) - \frac{1000M_0\left(1-\frac{C_{H_2O0}}{100}\right)\left(1-\frac{C_{VS0}}{100}\right)}{\left(1-\frac{C_{VSt}}{100}\right)} \tag{6}$$

The water reduction is calculated using

$$\eta = \frac{\Delta M_{H_2O}}{M_0} \tag{7}$$

RESULTS

Composting temperature

All of the treatments in the experiment reached the thermophilic phase on day 3 and maintained a temperature > 50°C for at least 5 days (Fig. 1). All of the treatments were in accordance with the safety standard.[22] The air temperature and saturated vapor pressure of water vapor are both higher. Thus, the same volume of air can remove more water molecules. Experimental evidence has indicated that higher pile temperatures accelerate water reduction during the composting process.[21]

In this study, the highest temperature in T1 to T4 was higher than that in T5 to T8, and the duration of the high temperature in T1 to T4 was significantly ($P < 0.05$) longer than that in T5 to T8. The turning mode in T1 to T4 was no turning, whereas T5 to T8 was turned during the temperature-increasing phase. The temperatures in T3, T4, T7, and T8 increased after turning in the thermophilic phase, indicating that turning may cause this second increase in temperature and maintain a high temperature. In the cooling phase, the higher turning frequency (every 2 days) caused the temperature to decrease, lower than that for the lower turning frequency (every 4 days), especially from day 16 to day 22.

Free airspace and pile settlement

The FAS and pile settlement were both indications of compaction. The FAS and pile settlement variations are present in Fig. 2. From day 1 to day 8, the FAS of each treatment first decreased and then increased to 35%, approximately, no significant effect on the FAS caused by turning was observed in the temperature-increasing phase ($P > 0.05$). The FAS increased to more than 55% rapidly after turning on day 8 or 12. In the cooling phase, different turning frequencies had no significant effect on the FAS ($P > 0.05$). Pile settlement occurred as soon as a composting pile was built until turned, and turning in the temperature-increasing phase delayed pile settlement from day 2. The pile height increased to approximate 1.55 m rapidly after turning on day 8 and day 12. In the cooling phase, different turning frequencies had no significant effect on pile height ($P > 0.05$).

Water reduction

The initial moisture and VS contents of all treatments were 65.40 ± 0.36–68.90 ± 0.24% and 63.00 ± 0.44–69.50 ± 0.31%, respectively. Large differences in the final moisture content (Table 2) were observed because of the different turning strategies. In particular, the final moisture content of T3 was <40%. A slight difference was observed in the final VS content in each treatment. The decrease in VS content in each treatment was approximately 7%. The water reduction was calculated using Equations (3)–(7), of which the values in T3 and T7 were 591.63 ± 6.79 kg ton^{-1} matrix and 484.91 ± 6.43 kg ton^{-1} matrix, respectively. The most efficient turning strategy was T3 (Table 1), which was turned once in the thermophilic phase and turned every 4 d in the cooling phase. The values of water reduction in T3 and T7 were much higher than those in the other treatments. T3 and T7 indicated that the turning strategies in both thermophilic and cooling phases were the same.

Significant differences in water reduction between the treatments were determined (Table 3). Differences were observed between T3 and T7 at 5% significance level. The differences of these two treatments from other treatments were also at 5% significance level. In contrast, no significant differences were observed between T2, T4, T5, T6, and T8.

DISCUSSION

Effect of different turning frequencies on removing water in each phase

In this study, water reduction was used to evaluate the effect of turning frequency on water removal in different phases during the whole period.

The range analysis results are shown in Table 4. The range value expresses the significance of the influence of the factors, and factors with a larger range have a bigger impact on the water reduction. According to the range value of each factor, the order of factor impact was as follows: cooling phase (164.27) > thermophilic phase (101.17) > temperature-increasing phase (75.99). The range of different turning modes in the cooling phase was the largest among all these ranges, implying that the different turning modes in the cooling phase was the most obvious factor influencing the moisture content of the final product.

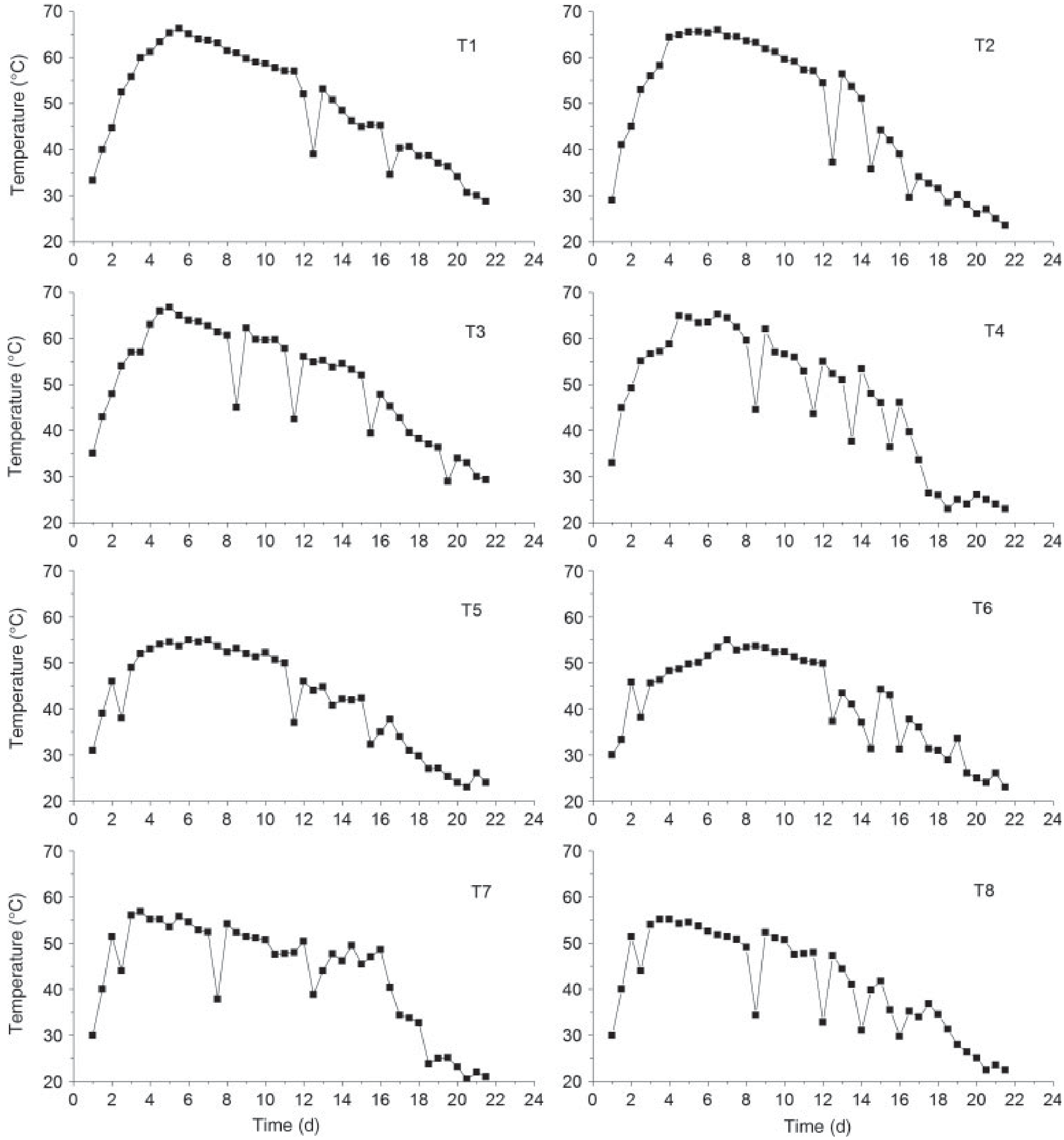

Figure 1. Temperature variation during the composting process under the different treatment regimes.

In the temperature-increasing phase, turning considerably affected the pile temperature. For the pile turned on day 2, there was no remarkable effect on the FAS and pile settlement, but its duration at high temperature was shorter than that for no turning, as shown in Fig. 1, the average duration of the thermophilic phase for T1–T4 was 234 h while that for T5–T8 was 174 h. Therefore, turning in the temperature-increasing phase caused increased heat loss. Besides moderate compaction, high pile temperature facilitates water evaporation from the SS composting pile,[19] thus, turning in the temperature-increasing phase had a negative influence on efficient water removal.

In the thermophilic phase, the pile was turned on day 7 or 8. At this time, the FAS and pile height were low before turning. After turning, the FAS and pile height increased rapidly. Turning accelerated the efficiency of aeration, and high temperature promoted water evaporation. Thus, turning once in the thermophilic phase has a favorable effect on water removal.

In the cooling phase, the values of FAS were significantly higher than those in the temperature-increasing phase and thermophilic phase ($P < 0.05$), and pile settlement was alleviated after each turning (Fig. 2). Cai[19] indicated that higher FAS and an uncompacted pile had favorable effects on water removal. Figure 2 also reveals that different turning frequencies in the cooling phase showed no significance ($P > 0.05$), and turning at a lower frequency reduced heat loss. The temperature after day 16

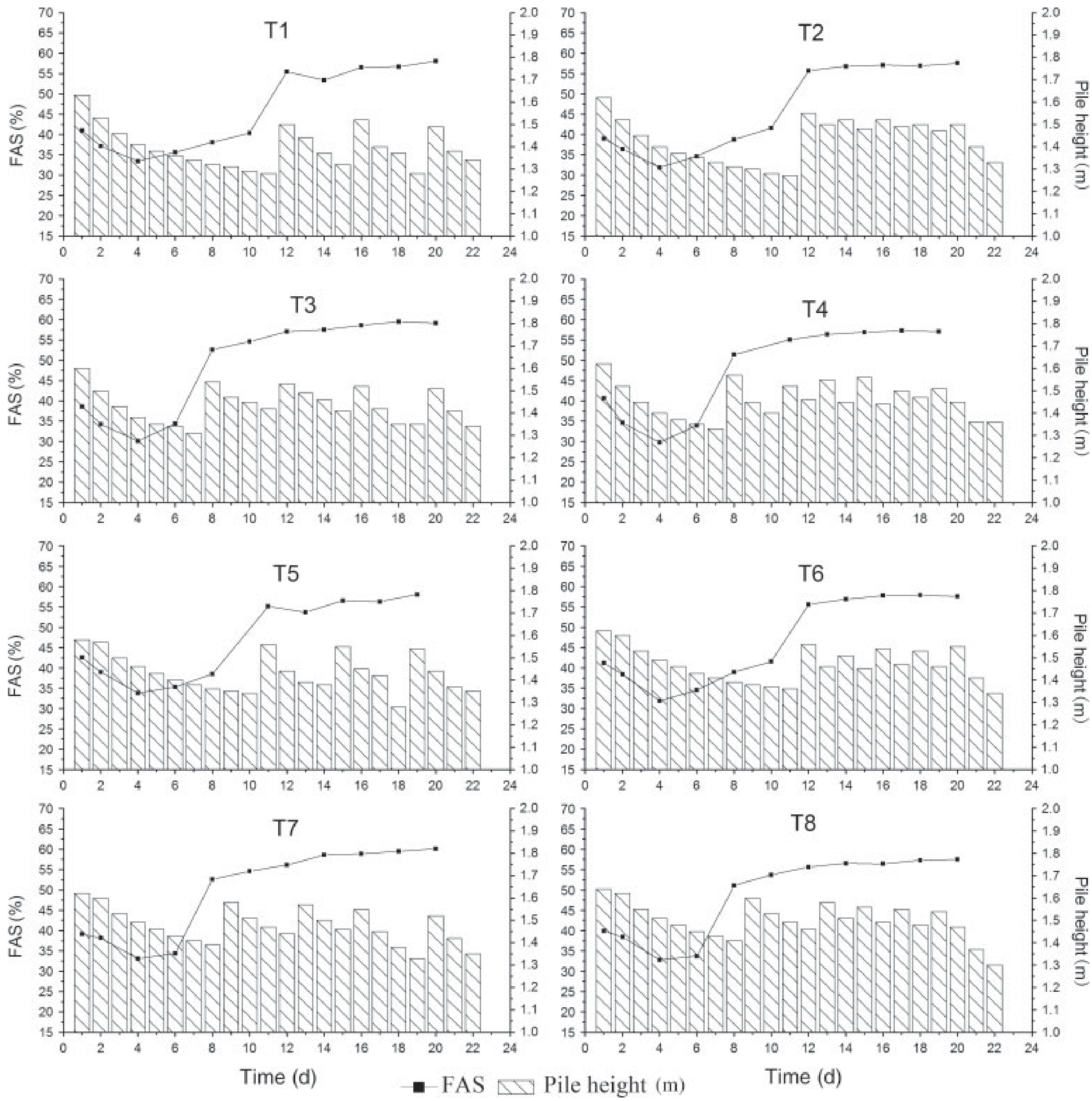

Figure 2. FAS and pile height variation during the composting process under the different treatment regimes.

Table 2. Change in moisture content, VS content, and total removed water in each treatment

	Initial moisture content (%)	Final moisture content (%)	Initial VS content (%)	Final VS content (%)	Initial pile weight (tons)	Water reduction (kg ton^{-1} matrix)
T1	67.90 ± 0.34	58.00 ± 0.69	63.48 ± 0.54	53.96 ± 0.78	207.1	374.88 ± 8.78
T2	68.10 ± 0.56	60.01 ± 0.87	63.00 ± 0.44	57.50 ± 0.91	201.6	294.00 ± 6.65
T3	68.90 ± 0.24	37.50 ± 0.79	69.50 ± 0.31	61.00 ± 0.87	197.4	591.63 ± 9.79
T4	67.46 ± 0.39	57.00 ± 0.94	65.00 ± 0.23	61.00 ± 0.96	193.0	312.37 ± 8.64
T5	67.50 ± 0.55	60.10 ± 1.01	63.70 ± 0.38	57.00 ± 0.69	205.3	298.02 ± 7.56
T6	66.98 ± 0.61	63.00 ± 0.87	63.48 ± 0.43	55.44 ± 0.65	194.9	251.65 ± 5.69
T7	67.50 ± 0.49	42.40 ± 0.95	63.00 ± 0.31	58.70 ± 0.88	199.1	484.91 ± 6.43
T8	65.40 ± 0.36	60.50 ± 0.75	65.50 ± 0.56	59.80 ± 0.86	198.7	234.34 ± 5.56

Table 3. Significant differences in total removed water in each treatment

Treatment	Water reduction (kg ton^{-1} matrix)	5% significant level	1% extremely significant level
T3	374.88 ± 8.78	a	A
T7	294.00 ± 6.65	b	A
T1	591.63 ± 9.79	c	A
T4	312.37 ± 8.64	cd	A
T5	298.02 ± 7.56	cd	A
T2	251.65 ± 5.69	cd	A
T8	484.91 ± 6.43	d	A
T6	234.34 ± 5.56	d	A

in the treatment using turning every 4 days in the cooling phase was significantly higher than in the treatment using turning every 2 days (Fig. 1), indicating that higher turning frequency decreased the temperature. In the cooling phase, turning frequently is not appropriate for water removal. This experiment revealed that turning every 4 d in the cooling phase is more efficient than turning every 2 days.

Interactions of the turning frequencies in each phase on water removal

In this experiment, each turning frequency in the different phases may not have worked independently from each other, and the turning frequencies in the different phases often combined with one another to work. The interactions of each turning frequency in different phases may have affected water reduction. ANOVA was used to determine each factor and the significance level of the interactions in orthogonal experiments. Table 5 shows the significance level of the different turning frequencies in the different phases considering first-order interaction.

The differences in water reduction for each turning condition in the thermophilic and cooling phase were extremely significant (Table 5; $P < 0.05$), and that of the temperature-increasing phase was significant ($P < 0.05$), which indicates that the different turning conditions in these three phases significantly change water reduction. Extremely significant differences ($P < 0.05$) were also observed in the interaction between thermophilic and cooling phases. The efficiency of water removal can be increased in a given pile under the following conditions: without turning in the temperature-increasing phase, turning every 4 days in the cooling phase, or turning once in the thermophilic phase.

In this experiment, the time of turning in the thermophilic phase was only 4 days earlier than the time of the initial turning in the cooling phase. Turning in the thermophilic phase increased FAS rapidly (Fig. 2) and turning every 4 days in the cooling phase reduced heat loss (Fig. 1); combination of the two modes has an extremely favorable effect on water removal. Thus, a significant difference was observed in the interaction between the thermophilic and cooling phases. Turning in the temperature-increasing phase does not affect the FAS or settlement in the thermophilic and cooling phases, furthermore, turning in the temperature-increasing phase 6 days earlier than turning in the thermophilic phase and 10 days earlier than turning in the cooling phase may decrease the interaction between phases. Thus, no significant difference was observed due to interaction between turning in the temperature-increasing phase and the other two phases for the different turning modes.

Table 4. Range analysis of total removed water for the different turning frequencies in the different phases

	Level 1*(sum)	Level 2 (sum)	Level 1 (mean)	Level 2 (mean)	Minimum	Maximum	Range
Temperature-increasing phase	1572.88	1268.92	393.22	317.23	317.23	393.22	75.99
Thermophilic phase	1218.55	1623.25	304.64	405.81	304.64	405.81	101.17
Cooling phase	1749.44	1092.36	437.36	273.09	273.09	437.36	164.27

*In the temperature-increasing phase, level 1 is not subjected to turning, level 2 is turned once; in the thermophilic phase, the levels are similar to those in the temperature-increasing phase; in the cooling phase, level 1 is turned every 4 days, whereas level 2 is turned every 2 days (unit is kg ton^{-1} matrix).

Table 5. ANOVA of water reduction for different turning frequencies in different phases

Source	Square sum	Degrees of freedom	Mean square	F-value	P
Temperature-increasing phase	11548.9602	1	11548.9602	2727.6391	0.0122*
Thermophilic phase	20472.7612	1	20472.7612	4835.2668	0.0092**
Interaction between temperature-increasing and thermophilic phases	536.9364	1	536.9364	126.8139	0.0564
Cooling phase	53969.2658	1	53969.2658	12746.487	0.0056**
Interaction between temperature-increasing and cooling phases	499.28	1	499.28	117.9202	0.0585
Interaction between thermophilic and cooling phases	20258.832	1	20258.832	4784.7409	0.0092**
Blank	4.234	1	4.234		
Error-term	4.234	1	4.234		

**Difference is significant at 0.01 level.
*Difference is significant at 0.05 level

CONCLUSION

Different turning strategies significantly affect water reduction in the pile during sludge composting. The water reductions in each treatment using different turning strategies were compared. The most efficient turning strategy for this process is as follows: no turning in the temperature-increasing phase, turning once in the thermophilic phase, and turning every 4 days in the cooling phase, for which the water reduction was 591.63 kg ton^{-1} matrix. The different turning modes in the three phases as well as the interaction between the thermophilic and cooling phases very significantly affect water removal.

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