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Abstract

The aim of this study was to determine the appropriate strategy for cattle manure composting with forced aeration. The composting of cattle manure was conducted using an 18.8 L reactor with three different amounts of total air supplied (1080, 3240 and 10800 L/kg dry mass) during 360 h of composting using continuous and on/off sequencing (20 min/h) aeration methods and three turning patterns (no turning, full turning and turning with position change). The degradation of organic matter in three-stage systems (the compost was turned every 120 h over the 360 h period) was significantly affected by total air supply volume and was large in the case of on/off sequence aeration. The pattern of moisture change was more affected by turning than by aeration modes. The optimal composting conditions for organic matter degradation (maximum of 37.7 %) were aeration rate: 0.45 L/min.kg-DM, aeration mode: on/off sequencing process and full turning. The total accumulated weight losses and heat generated during composting indicated significant effects of the total air supplied and were large in the case of the continuous process.

Keywords	composting; cattle manure; on/off aeration; turning; heat generated
Taxonomy	Process Technology, Biomass Utilisation
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1. Introduction

Composting is the preferred approach for dealing with waste problems from the animal husbandry sector. Forced aeration composting has several advantages, including short composting time, low space requirements and process control. The decomposition, heat production, heat balance and material temperature of compost were interrelated (Kimura, 2003). Availability of oxygen is the main factor affecting aerobic decomposition. Air is provided to the compost matrix by forced aeration, agitation and turning (Kreith, 1994). Turning during composting is usually done to minimize the heterogeneity associated with temperature, oxygen and moisture gradients in the systems (Vandergheynst and Lei, 2003). The air supply could be delivered by different aeration strategies (continuous or intermittent (on/off sequencing methods)) (Keener et al., 2001). On/off sequencing aeration is defined as the delivery of air in which the supply can be controlled by regulating the blower “on/off” using a timer control (Haug, 1993). The purpose of on/off sequencing in the composting of cattle manure is to save energy but still provide enough oxygen to decompose organic compounds.

The lower limit of aeration requirement was derived from the rate of oxygen consumption for organic decomposition. Iwabuchi and Kimura (1994) reported that the maximum oxygen uptake rate of dairy cattle manure at moisture content 76.7% (wet basis: WB) was 4.8 g/h.kg-volatile matter. Kimura (2003) suggested that aeration rates of 0.25 and 2.75 L/min.kg-(dry matter: DM) and a reactor volume of 0.7 L were suitable for composting of agriculture waste. Lau et al. (1992) recommended that aeration at 0.04–0.08 L/min.kg-(volatile matter: VM) was suitable for swine waste composting. The air requirement for drying and process temperature control is usually much greater than the requirement for biological oxidation (Haug, 1993).

There are a number of aeration control strategies that have been used in practice, or in some cases the aeration control strategy was not adequately detailed based on the laboratory data. Previous studies have applied continuous aeration methods for composting experiments (Lau et al., 1992; Elwell et al., 2001; Robertsson, 2002; Doshu, 2003, Karyadi et al., 2007, Guardia et al., 2012). Bari and Koenig (2000) and Bari et al. (2000) proposed the kinetic analysis of forced aeration. Bach et al. (1987) and Shimizu et al. (1989) proposed a model for fermentation and drying in composting that was satisfactory for prediction of dry matter degradation. Kimura et al. (2007) demonstrated using a small scale reactor that a relatively high ventilation rate and specific combination of intermittent aeration (ventilation/resting ratio by on/off sequencing method) could provide more effective composting than continuous ventilation. Comparison of models for continuous and on/off sequencing has not yet been undertaken. The mechanisms of the composting process by intermittent aeration are still unclear.

The objectives of this study were 1) to determine the effect of different turning and aeration treatments on the composting of cattle manure and 2) to evaluate these composting processes by total heat generated and organic matter degradation during the composting reaction.

2. Methods

2.1. Materials

Fresh manure (beef cattle) and sawdust were collected from the Nippon Agricultural Research Institute (Tsukuba, Ibaraki Prefecture, Japan). The initial moisture contents of the fresh manure and sawdust were 78%–80% and 12%–18% (WB), respectively. The organic matter contents of the manure and sawdust were 88% and 99%, respectively. Sawdust was added to the cattle manure to adjust the moisture content to from 60.7% to

65% (WB), providing a suitable initial moisture content to begin composting (Torisu et al., 1980; Kimura and Shimizu, 1981). Raw materials were collected for every run and the manure was stored in the laboratory for one day before the experiment to measure the initial moisture content.

2.2. Compost reactor

The compost reactor had a total capacity 18.84 L and was fabricated using 20 cm-diameter polyvinyl chloride (PVC) pipe, with each layer 15 cm high. The compost reactor was made by stacking four layers on top of each other, as shown in Fig. 1. There was a plenum chamber in the bottom layer. Each layer had wire mesh (1 × 1 mm) at the bottom. The advantage of the wire mesh is that it facilitates sampling without mixing with the other layers. The reactor received forced aeration from an air pump (Sinku-Kiko DAP-30) with a 30 L/min capacity through a 5 mm-diameter flexible pipe. We used an air flow meter (Kolfoc) with capacities of 0.5, 2.0 and 10.0 L/min. A programmable timer was utilized for intermittent mode. The outer surface and bottom of the compost reactor were insulated with 10 cm thick wool fiberglass to reduce heat loss. The temperatures were measured with a thermocouple (T type). The thermocouple was inserted through a small hole (4 mm) in the PVC pipe in each layer. Temperature data were recorded with a data recorder (Keyence NR 1000) with a time interval of 30 min. A personal computer was connected for data acquisition, to display the temperature and for recording onto a hard disk.

2.3. Experimental design

About 8 kg of the mixture of cattle manure and sawdust was placed in the compost reactor; each layer could hold 2 kg of raw material. Experiments were performed without replication. Three total air supply (1.08, 3.24 and 10.8 m^3/kg-DM) amounts were delivered within 360 h of composting by continuous and intermittent methods. Three aeration rates of 0.05, 0.15 and 0.50 L/min.kg-DM were applied by the continuous method, while three aeration rates of 0.15, 0.45, and 1.50 L/min.kg-DM for 20 min/h were applied for the intermittent method, as shown in Fig. 2. Run 0.15 Ai, 0.45 Ai and 0.15 Ci were not carried out. These aeration rates were selected to facilitate high-temperature composting (Kimura and Shimizu, 1981). Three turning patterns (types A, B, and C) were applied (Kayadi et al., 2007). Type A compost underwent no turning. The compost material for type B was placed on a plastic bucket and it was turned using a scoop. The compost material for type C was removed from each layer, turned, and then replaced in the same vessel (Fig. 3). The positions of the layers were reversed from the previous period. The compost was turned every 120 h; samples were collected before turning. The runs were codified as follows, run 0.15Bc; in this code the numbers denoted to the aeration rate (L/min.kg-DM), the capital letters denoted the turning type (A, B or C, as above) and the small letters of c or i denoted continuous or intermittent aeration methods, respectively.

2.4. Measurements

The moisture content of raw materials and composting mixtures was determined by drying the samples at 105 °C for 24 h in an oven (Eyela, WFO-600SD, Japan). Ashes were obtained by placing 4 g of dry sample in a muffle furnace (ISUZU, Taiyou, Japan) at 600 °C for 3 h and the organic matter was calculated as the difference between the ashes and the dry weights. The weight of each layer was measured with a balance (Mettler-Toledo, BD 6000, Japan). The moisture reduction, organic matter reduction and degradation were defined as follows:

$$Moisture\ reduction\,(\%) = \frac{(MC_i - MC_f)}{MC_i} \times 100\% \qquad (1)$$

$$Organic\,matter\ reduction\,(\%) = \frac{(OM_i - OM_f)}{OM_i} \times 100\% \qquad (2)$$

$$Degradation\,(\%) = \left\{1 - \frac{(100 - OM_i)}{(100 - OM_f)}\right\} \times 100\% \qquad (3)$$

2.5. Composting model

The model of decomposition and the drying process (Shimizu et al., 1989) is shown in Eqs. (4). This model was used to calculate the heat generated from the composting process.

$$E = hm \bullet \Delta D = \sum \begin{Bmatrix} (\Delta\theta.\gamma.Q.C_{pa}(T_{ac(n,i)} - T_{ac(n,i-1)})) + \\ \Delta\theta.\gamma.Q(H_{wc(i)} - H_{wc(i-1)})q_e + \\ W_{(n-1,i)}C_{pm}(T_{mc(n,1)} - T_{mc(n-1,i)}) \end{Bmatrix} \qquad (4)$$

Heat loss compensation from the wall and the top layer was calculated using the same formula as in Shimizu et al. (1989).

3. Results and discussion

3.1. Temperature distribution

The temperature course started without a long lag phase (Fig. 4). Temperature rose quickly to the mesophilic phase and then to the thermophilic phase. As the aeration rate increased, the time required to reach both phases decreased. The maximum temperatures for the continuous method at aeration rates of 0.05, 0.15 and 0.50 L/min.kg-DM were 64.2, 73.2 and 70.8 °C, respectively, while the maximum temperatures for the intermittent method at aeration rates of 0.15, 0.45 and 1.50 L/min.kg-DM were 55, 74 and 69.0 °C, respectively (Table 1). The highest temperature occurred in the first period for all runs, most likely because of the large amount of fresh substrate in the initial stage of composting, in which susceptible organic materials (e.g., sugars, starches, amino acids and nucleic acids) were easily decomposed (Epstein, 1997).

The effect of intermittent aeration on the temperature distribution for the total air supply of 3.24 m^3/kg-DM is shown in Fig. 4 for runs 0.15Bc, 0.45Bi, and 0.45Ci. In run 0.15Bc, the temperatures in the second and third layers were high during composting. When oxygen was delivered by intermittent aeration (as in runs 0.45Bi and 0.45Ci), the temperature in the first and fourth layers increased. This proved that intermittent aeration could reduce the cooling effect by reducing heat removal by aeration during the ‘no aeration’ period. The effect of intermittent aeration with total air supply of 10.8 m^3/kg-DM on the temperature distribution is shown in Fig. 3 for runs 0.50Bc, 1.50Bi, and 1.50Ci. These patterns were different when compared with the previous figure, in which the temperature distribution in run 0.50Bc was similar to those in runs 1.50Bi and 1.50Ci. The temperature in the first layer was the lowest among the layers in the vertical direction. The aeration mode of 20 min/h for all aeration rates did not affect the decrease in temperature. This means that stopping aeration for 40 min of each hour still provided enough oxygen for decomposition. Temperature of the composting piles was not controlled by aeration alone, but by a combination of aeration rate, frequency and duration of aeration (Lau et al., 1992).

The value of the rate of temperature increase indicates the kinetic reaction during composting. The maximum rates of temperature increase for the continuous aeration rates of 0.05, 0.15, and 0.50 L/min.kg-DM were 2.4, 3.1, and 4.8 °C/h, respectively. The maximum rates of temperature increase for the intermittent aeration rates of 0.15, 0.45 and 1.50 L/min.kg-DM were 1.6, 2.3, and 3.5 °C/h, respectively. The rates of temperature increase for the intermittent method were lower than those for the continuous method, which is most likely because the availability of oxygen was not continuous. The heating rates after the first and second turnings were less than in the early stage of composting.

In this study, aeration was supplied at a constant aeration rate throughout the composting period. Haug (1993) suggested that lower aeration after the peak temperature was observed could enhance the composting process. Lowering the aeration rate after the peak temperature was obtained might reduce the heat loss by aeration, but at temperature exceeding 60 °C, the optimum for most thermophiles is reached, and system starts to limit itself due to the inhibitory high temperatures (McKinley and Vestal, 1984). Need to be turning the compost matrix make to release heat from the inner compost, which temporarily cools it down.

3.2. Moisture content

The initial moisture content of the mixture of cattle manure and sawdust varied from 60.7% to 66.5%. Table 2 lists the initial and final moisture contents of the composted material. The 40 – 60% moisture range is a general recommendation that works well for most materials (Chowdhury et al, 2013). The initial moisture content for the compost materials for six experiments are higher than 65%, but the acceptable upper moisture limited may be maintained well the porosity in the compost matrix by used the mixture of cattle manure and sawdust. Thus, the moisture content difference are neutral for the whole composting periods. There were different patterns observed for the continuous and intermittent aeration treatments. For the continuous method, the decrease in moisture content was higher for composting without turning than that for composting with turning. On the contrary, for intermittent aeration similar reductions in moisture content were observed for runs 0.15Bi, 0.45Bi and 0.45Ci. For the aeration rate of 1.50 L/min.kg-DM, the moisture reduction was similar for both B and C turning methods.

The moisture content change during composting in continuous and intermittent treatments is shown in Fig. 5. For all runs, the moisture content decreased in the first 120 h of composting. In run 0.45Bi, the moisture contents at 120 h in the first, second, third and fourth layers were 54.4%, 57.9%, 58.4%, and 60.4%, respectively; there was a moisture content gradient among the layers because of the vertical direction of the air flow. The average moisture contents for the same run at 0, 120, 240 and 360 h were 62.9%, 57.7%, 60.4%, and 61.1%, respectively. Moisture contents increased after 120 h most likely because of turning in both the continuous and intermittent methods. For continuous and intermittent methods of composting without turning, the moisture content decreased throughout the composting time; these results were similar to the finding by Lau et al. (1992) and Hong et al. (1983). Viel et al. (1987) reported that the moisture content of compost material at the end was higher than the initial value; water release through microbial activity then outweighed evaporation. In these results the final moisture content was still sufficient for biological activity. Decomposition of organic matter requires the presence of moisture to support microbial activity. Moisture contents lower than 40% inhibit microbial growth and degradation of organic matter (Epstein, 1997).

The disadvantage of a low aeration rate is that leachate occurred in the base of compost material and dropped into the plenum chamber. Leachate was not found for the intermittent aeration rate of 0.45 L/min.kg-DM.

3.3. Organic matter

The initial and final organic matter content of the compost material was listed in Table 3. The highest reduction in organic matter (4.3%) occurred in run 0.45Bi. The temperature distribution in 0.45Bi showed that the maximum and average temperatures during turning to turning and during whole composting periods is almost highest of all experiments (Table 4). The smallest reduction in organic matter (0.50%) occurred in run 1.50Ai. Excess aeration in run 1.50Ai resulted in low organic matter degradation, which might have been caused by low maximum temperature and average temperature and resulting in drying during whole composting period.

In the active composting phase easily decomposable and putrescible compounds are broken down and pathogens can be eliminated (Epstein, 1997). During the curing phase the compounds less susceptible to carbon mineralization are broken down along with fatty acids. The effect of aeration method and turning on the organic matter degradation was shown in Table 5. Using the continuous method, increasing aeration within the range of 0.05 to 0.50 L/min.kg-DM enhanced the organic matter degradation from 10.3% to 30.1%. For the intermittent method, increasing aeration from 0.15 to 0.45 L/min.kg-DM increased the organic matter degradation from 28.1% to 37.7%, but further increasing the aeration from 0.45 to 1.50 L/min.kg-DM reduced the organic matter degradation to 32.1%.

Veeken et al. (2002) reported that because of mixing during 360 h of composting with turning, total solids and volatile solids of the turned reactor showed no gradient over the height of the reactor. Large differences in moisture content were observed for undisturbed reactors. Robertsson (2002) reported that pH decreased faster and to a greater extent the earlier the air supply was turned off; volatile organic acids were found in compost where the air supply had been turned off. If aeration was resumed, the composting process started again. The duration and maximum temperature of re-activated compost will be determined by how much microbial available energy is left in the compost material when the air supply is turned off.

The decomposition in the full turning treatment was higher than in the turning with position change in both the continuous and intermittent aeration methods. The purpose of reversing the direction of layers along the vertical plane was to provide a more uniform oxygen supply for all layers compared with composting without turning; this method still resulted in lower organic matter degradation when compared with the full turning treatment. This is most likely because the compost material is more uniform with full turning than with turning with position change.

From visual inspection, actinomycetes were found in high abundance in run 0.45Bi. This agrees with Vandergheynst and Lei (2003), that actinomycetes develop when compost is maintained at >40 °C for a long time. These microorganisms are responsible for converting hemicellulose and cellulose to more readily degradable substrates such as starch and sugar. Bacteria dominate the early composting stage and fungi are inactivated at temperatures over 60 °C (Bernal et al., 2009). The visual evidence of filamentous colonies is usually limited when mechanical action is frequent (Haug, 1993).

The effects of the combination of aeration rate and turning on total weight loss were shown in Fig. 6(a) and (b). As aeration increased the total weight loss increased. Elwell et al. (2001) reported that 75% of weight loss was because of water removal. Within the range of the aeration rates from 0.05–0.50 L/min.kg-DM, increased aeration rate was positively correlated with water loss and organic matter degradation. Intermittent aeration for 1.50 L/min.kg-DM was the critical condition for enhanced organic matter degradation. High aeration tends to form channels within compost material; turning then functions to break down the channel formation and provide more uniform distribution of aeration.

Previous studies have reported suitable ranges of aeration rate for composting. Our results indicated that the combination of aeration rate, aeration methods and turning resulted in specific patterns in the composting process. Intermittent aeration allowed the efficient microbial use of oxygen. Another effect of intermittent aeration was that heat removal by aeration could be stopped or reduced and that high temperature in the compost material facilitated extensive decomposition of organic matter. The effect of turning on composting with low aeration rates was not significant. The application of turning and suitable aeration produced rapid decomposition of organic matter. The highest organic matter degradation was obtained in composting with an intermittent aeration rate of 0.45 L/min.kg-DM and with full turning (type B).

The accumulated weight loss during composting was found to be significantly correlated with total air supply and was most important in the continuous aeration process. The total weight loss in run 0.50Cc was 25%, while total weight loss of run 1.50Bi was 20.5%. This might be because of physical factors, as the water removal by continuous aeration is steady throughout the composting period in comparison with intermittent aeration methods. Elwell et al. (2001) found that the total weight loss during 400 h of swine waste composting was 41.4%–53.2%. The difference might be because the temperatures of the 1st stage in runs 0.45Bi and 0.45Ci were higher than those in runs 1.5Bi and 1.5Ci, because of heat loss from the high amount of aeration volume in the latter runs.

The mechanism of turning has been reported by Cayuela et al. (2006) and Solano et al. (2001). Solano et al. (2001) reported that cellulose organic matter degradation for composting with turning was higher than that for composting with forced aeration. Doshu (2003) reported that organic matter degradation of cattle manure in a composting facility could be increased from 44.3% for continuous aeration to 55.0% for intermittent aeration (4.7 h/day) over six weeks of composting; another advantage was the length of time that the temperature was over 60 °C increased from 0 h for continuous aeration to 454 h for intermittent aeration. Viel et al. (1987) reported that organic matter from a mixture of cattle slurry and ground straw could be reduced by up to 50% during 120 days composting, and by 30% for a mixture of sewage sludge and sawdust by using in-vessel composting.

The composting process involves the fermentation and drying process. The desired outcome of composting is high rates of fermentation and drying, leading to substantial reduction in total mass. Rapid drying by excess aeration results in 'fake' compost since the material is stable with a low moisture content (Haug, 1993). In composting without turning moisture content tends to decrease. Water production was calculated by assuming water generated per 1 kg of dry matter was 0.57 kg as represented by the oxidation reactions of $C_6H_{12}O_6$ and $C_5H_{12}O_5$, while water loss was calculated from the difference between total water loss and water production (Kimura and Shimizu, 1989).

With regards to mass transfer, the ratio of water loss to water produced is an indication of the condition of the composting process. If water loss is higher than water production, the moisture content decreases. Intermittent aeration provided the lowest ratio of water loss to water production, because of high water production. Turning reduced the ratio of water loss to water production. The reason for this is that turning re-forms the compost matrix and facilitates further decomposition resulting in higher water production.

The effect of aeration and turning methods on the ratio of water loss to water production is shown in Fig. 6(c) and (d). In composting without turning with continuous aeration, the ratio of water loss to water production was relatively high. On the contrary, in composting with turning with intermittent aeration, the ratio of water loss to water production was relatively low. Excess drying was observed in run 1.50Ai, where the ratio of water loss to water production was very high. The aeration rate of 1.50 L/min.kg-DM with intermittent aeration without turning resulted in low organic matter degradation and high water removal by aeration.

3.4. Effectiveness of aeration

The energy utilized in the composting process is mostly related to the power consumed in providing aeration. In this study, energy for turning was not considered. The energy required for forced aeration composting is a modest amount when compared with the energy and manpower required for turned composting methods (Tiquia and Tam, 1998). The assumptions of using this model were that latent heat was constant, heat loss by radiation was neglected and the heat capacity of the compost material was constant.

With the same total aeration (3.24 m^3/kg-DM), the organic matter degradation for run 0.45Bi (37.7%) was higher than that for run 0.15Bc (23.9%). For continuous aeration, the highest organic matter degradation was obtained in run 0.50Bc (30.1%); to achieve the same organic matter degradation, power consumption for aeration could be reduced by 66.7% by applying intermittent aeration. In other words, intermittent aeration after turning enhanced the organic matter degradation and reduced the energy requirements by two thirds compared with continuous aeration.

The effect of aeration and turning method on heat generated during composting was shown in Table 6. The results of run 0.15Bc were used as the reference value for calculating the heat increase of other treatments. The results showed that the material temperature during the intermittent aeration process could be maintained by heat from the composting reaction. Increased heat generated after turning at 120 h of composting indicated the effect of turning on organic matter degradation (Fig. 7(a) and (b)). The calorific values from composting obtained in previous studies were 13.5–13.8 kJ/g total solid (Ahn et al., 2007) and 13.0 kJ/g (Shimizu et al., 1989). The amounts of heat generated by the compost reaction were 4.6 and 4.12 $\times$ 10^3 kJ for continuous and intermittent aerated systems, respectively. Degradation of organic matter in the compost material increased with increasing air supply volume under continuous aeration (Fig. 8(a)); the degradation rate was higher with intermittent than continuous aeration for the equivalent air volume. The optimum volume of total air supplied under intermittent aeration was 3.24 m^3/kg-DM (Fig. 8b). Temperature indicated the composting activity, and further analysis of heat generated from different modes of operation showed the effect of those treatments. The highest organic matter degradation and heat generated was obtained with 0.45 L/min.kg-DM, intermittent aeration and full turning. The organic matter degradation in three-stage systems (by turned composting material) was significantly affected by total air supply volume, in particular for intermittent aeration. The compost process in a packed-bed reactor using various air supply methods could be evaluated by the heat generation and the organic matter degradation.

4. Conclusions

This study compared aeration rate, aeration method and turning method to determine optimal composting conditions for cattle manure. Three rates of air supply were applied with continuous or intermittent aeration resulting in distinct patterns of moisture content, organic matter degradation and total weight loss in each treatment; the range of aeration rates covered very low and excessive aeration. Intermittent aeration after turning enhanced the organic matter degradation and reduced the energy requirements by two thirds compared with continuous aeration. The composting and drying model showed satisfactory results for continuous and intermittent aeration.

Appendix:

Cpa : heat capacity of air, kJ/kgK

Cpm : specific heat of sample, kJ/kgK , 3.00 kJ (Torisu et al., 1980)

ΔD : dry matter weight degradation, kg

E : heat generated, kJ

H : absolute humidity, kgH_2O/kgdry air

hm : caloric value, kJ/g, 13.0 kJ/g (Shimizu et al., 1989)

MC_i : initial moisture content, %

MC_f : final moisture content, %

OM_i : initial organic matter, %

OM_f : final organic matter, %

Q : airflow rate, L/h

$T_{(n,i)}$: temperature of layer i at time θ_n, °C

TQ : total air supply, m^3/kg-DM

W : weight of compost, kg

γ : air density, kg/m^3

q_e : latent heat of water vaporization, kJ/kgH_2O, 2.261 kJ/kgH_2O

θ : time, h

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FIGURE CAPTIONS

Fig. 1. Compost reactor setup.

Fig. 2. Three total air supply aeration level applied by continuous process (top) and on/off sequencing process (bottom).

Fig. 3. Schematic diagram of the turning pattern for runs A, B and C (T = Turning).

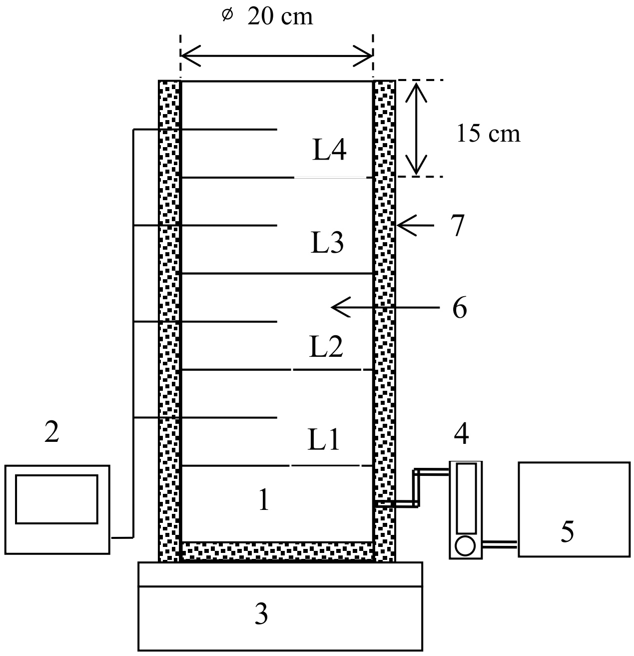
Fig. 4. Temperature profiles of compost matrix in a packed-bed reactor with two types of aeration mode (continuous and on/off sequencing) and turning (A, B, C). (: L1; : L2; : L3; : L4; : room; : turning). 0.05 Ac, 0.15 Ac, 0.15 Bi, 1.50 Ai and 1.50 Ci were not shown with ambient temperatures.

Fig. 5. Change in moisture content of compost matrix during processes in a packed-bed reactor with two types of aeration mode (continuous and on/off sequencing) and turning (A, B, C).

Fig. 6. Total air supply with aeration mode (continuous; on/off sequencing) and turning (A, B, C) vs. accumulated weight loss (a) continuous aeration; (b) intermittent aeration, and ratio water loss to water production (c) continuous aeration; (d) intermittent aeration.

Fig. 7. Heat generated from compost matrix in a packed-bed reactor with two types of aeration mode (continuous and on/off sequencing) and turning (A, B, C).

Fig. 8. Organic matter degradation vs. total air supply (a) continuous aeration; (b) intermittent aeration.



Notes

1. Plenum chamber
2. Data recorder
3. Balance
4. Air flow meter
5. Air pump
6. Compost material
7. Heat insulator

Fig. 1. Compost reactor setup.

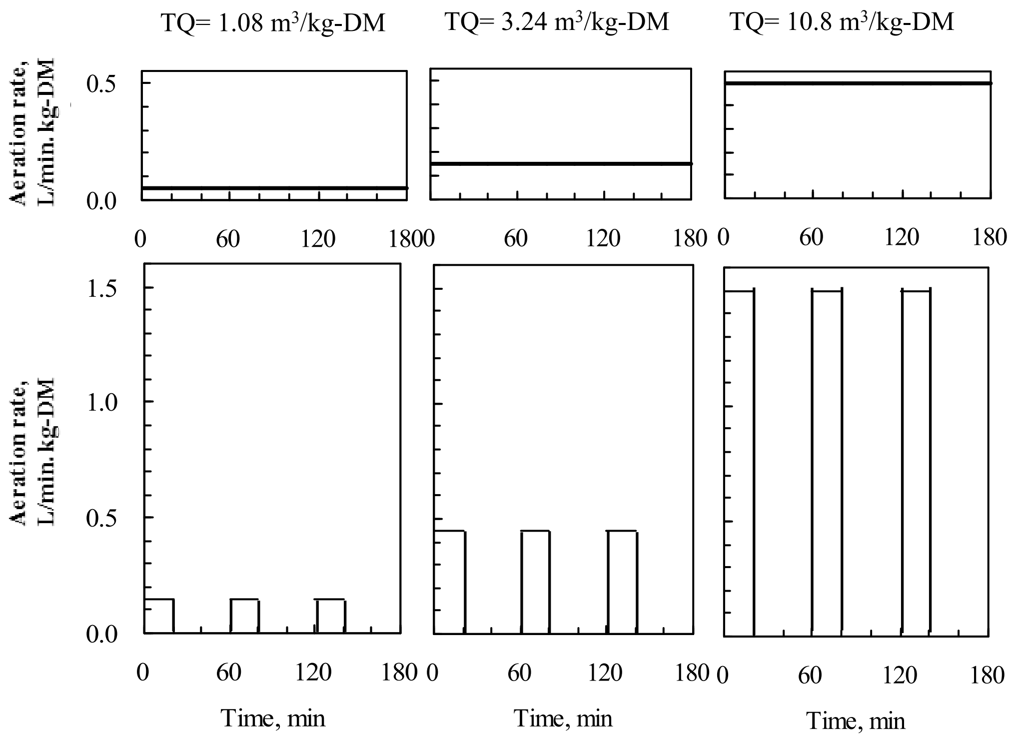
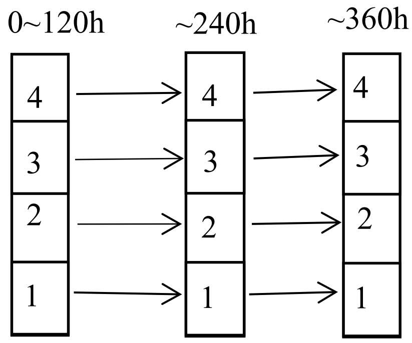
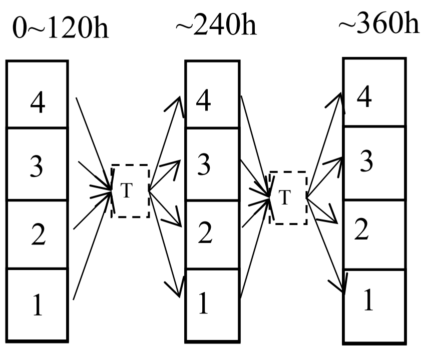


Fig. 2. Three total air supply aeration level applied by continuous process (top) and on/off sequencing process (bottom).

A. No turning



B. Full turning



C. Turning and position change

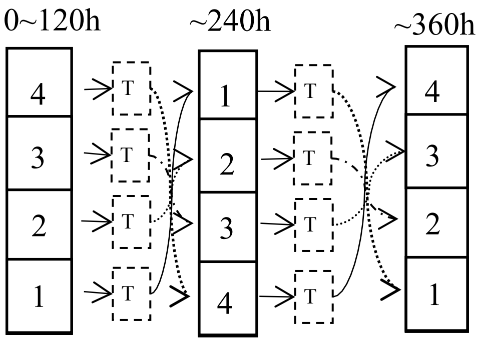


Fig. 3. Schematic diagram of the turning pattern for runs A, B and C (T = Turning).

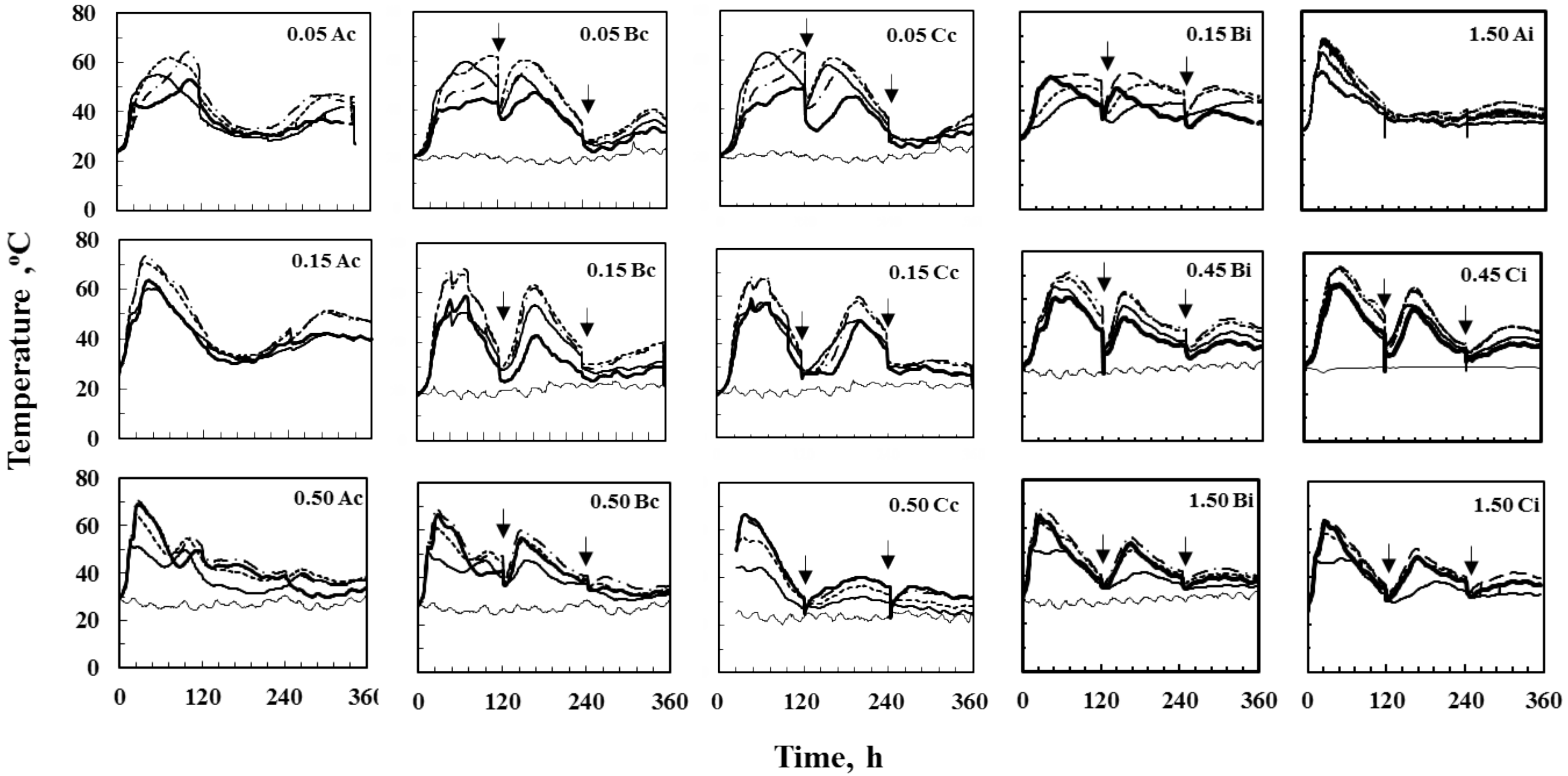
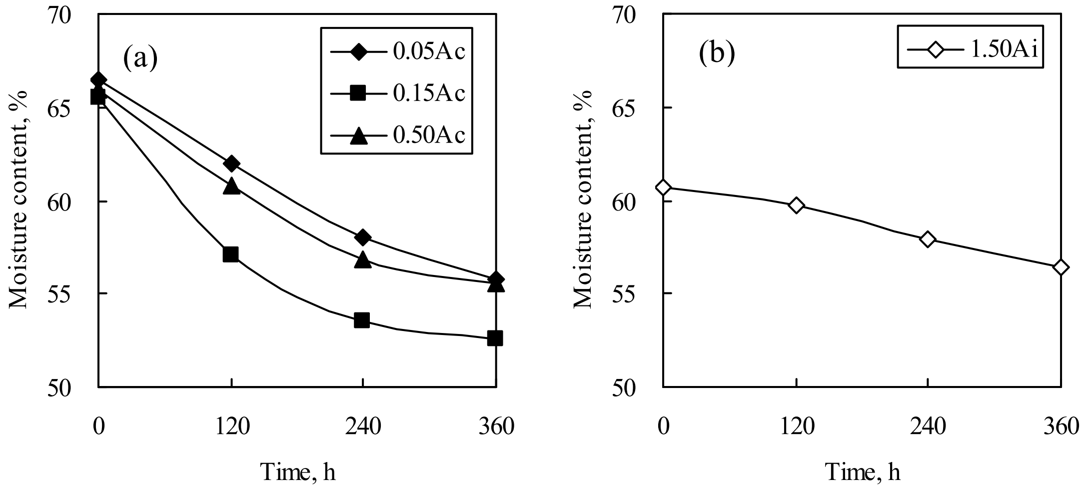


Fig. 4. Temperature profiles of compost matrix in a packed-bed reactor with two types of aeration mode (continuous and on/off sequencing) and turning (A, B, C). (____: L1; ...... : L2; _._._.: L3; ▬▬ : L4; ____ : room; →: turning). 0.05 Ac, 0.15 Ac, 0.15 Bi, 1.50 Ai and 1.50 Ci were not shown with ambient temperatures.

Without turning



Turning type B

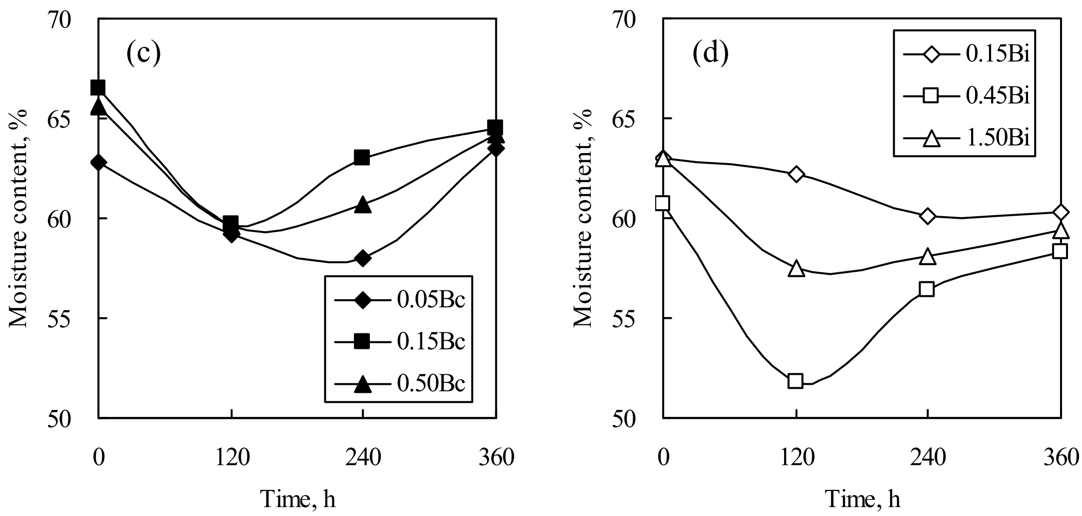


Fig. 5. Effect of total air supply with aeration modes (continuous and on/off sequencing) and turning on moisture content in compost material.

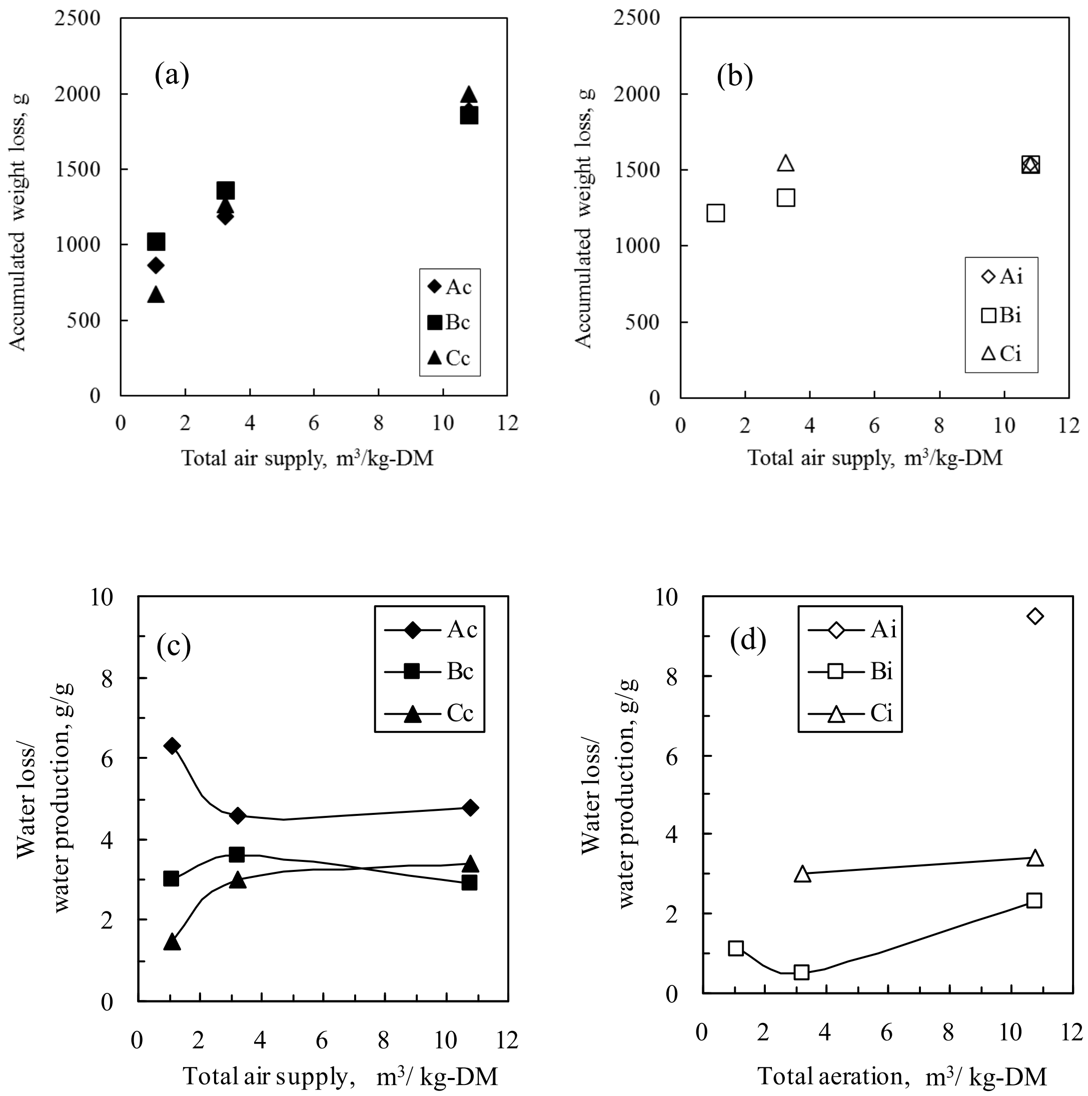


Fig. 6. Total air supply with aeration mode (continuous; on/off sequencing) and turning (A, B, C) vs. accumulated weight loss (a) continuous aeration; (b) intermittent aeration, and ratio water loss to water production (c) continuous aeration; (d) intermittent aeration.

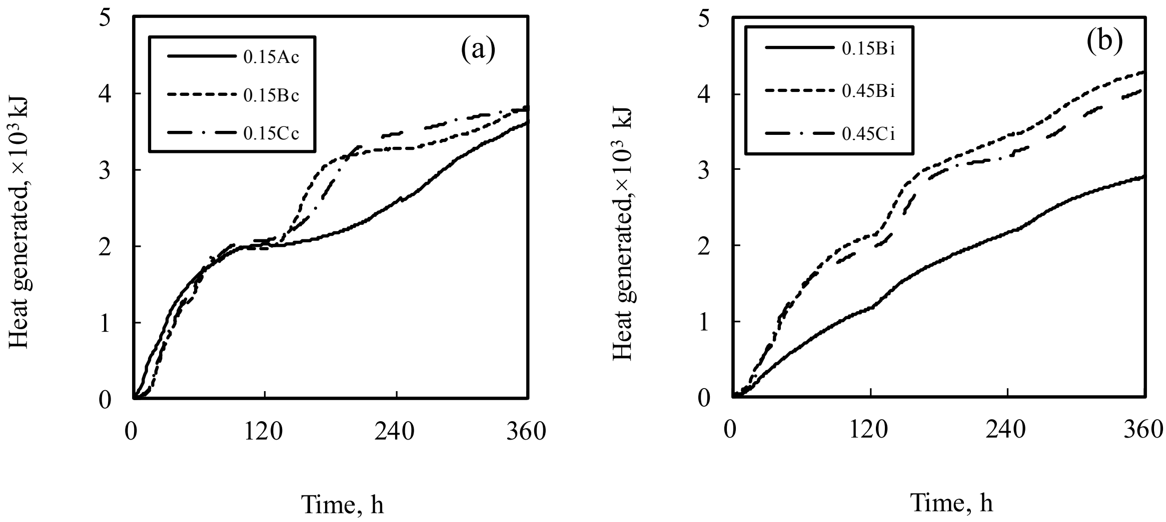


Fig. 7. Heat generated from compost matrix in a packed-bed reactor with two types of aeration mode (continuous and on/off sequencing) and turning (A, B, C).

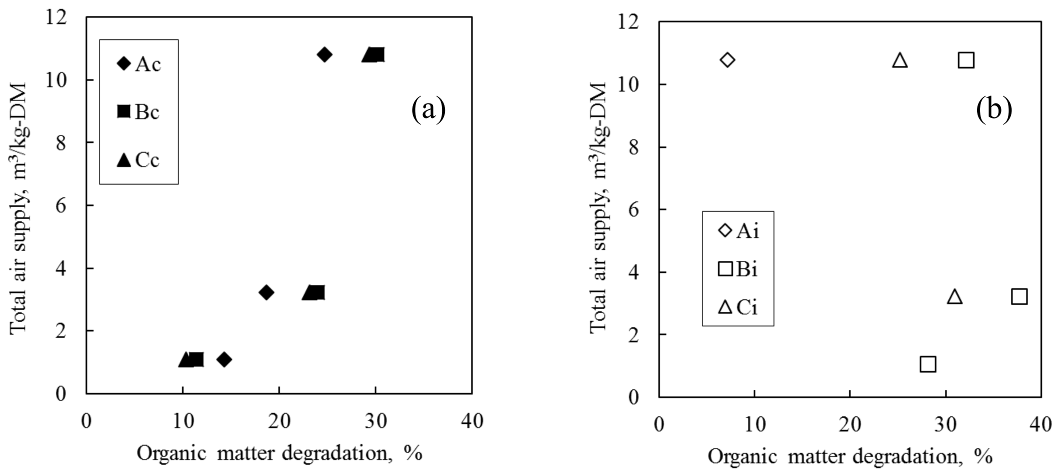


Fig. 8. Organic matter degradation vs. total air supply (a) continuous aeration; (b) intermittent aeration.

TABLES

Table 1
The maximum and average temperatures of compost material during whole composting period.

Table 2
The initial and final moisture content of compost material for compost reaction.

Table 3
The initial and final organic matter of compost material for compost reaction.

Table 4
The maximum and average temperatures of compost material during turning to turning.

Table 5
The organic matter degradation (%) of compost material for compost reaction.

Table 6
Effect of force aeration mode and turning on heat generated.

Table 1

The maximum and average temperatures of compost material during whole composting period.

Aeration rate, L/min.kg-DM	Turning Method					
	Maximum temperature, °C			Average temperature, °C		
	A	B	C	A	B	C
Continuous						
0.05	64.2	62.0	64.3	40.0	40.2	40.4
0.15	73.2	69.9	68.4	44.1	39.8	39.2
0.50	70.8	68.9	66.5	42.1	43.2	42.1
On/off sequencing						
0.15	-	55.0	-	-	44.3	-
0.45	-	71.2	74.0	-	49.6	48.8
1.50	69.0	68.4	64.1	41.7	44.4	41.1

Table 2

The initial and final moisture content (%) of compost material for compost reaction.

Aeration rate, L/min.kg-DM	Turning Method					
	Initial			Final		
	A	B	C	A	B	C
Continuous						
0.05	**66.4**	**62.8**	**62.8**	**55.7**	**63.6**	**65.9**
0.15	**65.5**	**66.5**	**66.5**	**52.6**	**64.5**	**66.7**
0.50	**66.0**	**65.6**	**66.0**	**55.5**	**64.2**	**62.3**
On/off sequencing						
0.15	-	**63.0**	-	-	**60.3**	-
0.45	-	**60.7**	**63.0**	-	**58.3**	**61.1**
1.50	**60.7**	**63.0**	**65.4**	**56.5**	**59.4**	**59.8**

Table 3

The initial and final organic matter of compost material for compost reaction.

Aeration rate, L/min.kg-DM	Turning Method					
	Initial			Final		
	A	B	C	A	B	C
Continuous						
0.05	93.4	92.3	92.3	92.2	91.3	91.4
0.15	92.8	92.0	92.0	91.2	89.4	89.5
0.50	94.0	93.6	94.0	92.0	90.9	91.5
On/off sequencing						
0.15	-	94.6	-	-	92.5	-
0.45	-	93.6	94.6	-	89.7	92.3
1.50	93.6	94.6	94.2	93.1	92.1	92.3

Table 4

The maximum and average temperatures of compost material during turning to turning.

Aeration rate, L/min.kg-DM	B						C					
	Maximum temperature, ° C			Average temperature, ° C			Maximum temperature, ° C			Average temperature, ° C		
	1	2	3	1	2	3	1	2	3	1	2	3
Continuous												
0.05	**62.0**	**60.4**	**37.5**	**43.8**	**45.7**	**31.0**	**64.3**	**60.7**	**37.5**	**45.9**	**46.0**	**29.2**
0.15	**69.9**	**61.7**	**39.0**	**46.1**	**42.3**	**29.8**	**68.4**	**53.6**	**33.1**	**46.6**	**41.0**	**31.0**
0.50	**68.9**	**60.0**	**40.4**	**49.2**	**45.6**	**34.6**	**66.5**	**40.3**	**32.0**	-	-	-
On/off sequencing												
0.15	**54.7**	**55.0**	**46.4**	**44.8**	**45.2**	**42.9**	-	-	-	-	-	-
0.45	**71.2**	**63.2**	**51.6**	**55.3**	**49.1**	**44.1**	**74.0**	**65.1**	**48.5**	**55.8**	**42.2**	**42.6**
1.50	**68.4**	**56.2**	**43.2**	**50.5**	**43.7**	**38.6**	**68.2**	**56.4**	**43.2**	**46.8**	**40.1**	**35.9**

Table 5
The organic matter degradation (%) of compost material for composting reaction.

Aeration rate,	Turning Method		
L/min.kg-DM	A	B	C
Continuous			
0.05	14.3	11.4	10.3
0.15	18.6	23.9	23.1
0.50	24.7	30.1	29.3
On/off sequencing			
0.15	-	28.1	-
0.45	-	37.7	30.9
1.50	7.20	32.1	25.2

Table 6
Effect of force aeration mode and turning on heat generated.

Aeration rate, L/min.kgdm	Heat generated, $\times 10^3$ kJ			Heat increase, %		
	A	B	C	A	B	C
Continuous						
0.05	2.66	3.93	4.08	-26.4	8.74	12.8
0.15	3.62	3.81	3.79	0.00	5.45	4.89
0.50	4.15	4.60	-	14.8	27.1	-
On/off sequencing						
0.15	-	2.30	-	-	-42.0	-
0.45	-	4.30	4.06	-	18.9	12.2
1.50	3.23	4.12	4.01	-10.7	13.9	10.8

A, B, C are Turning Method