Thermophilic composting of food waste

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Abstract

A laboratory reactor was designed to study the effects of operating parameters (air suction rate, seeding and agitation) on the composting process of a synthetic food waste made of dog food. Experimental results showed that the synthetic food waste could be composted within 4 days and the final compost passed the maturity tests. In most cases except those with 32% of seeding, the process involved two major stages of composting. The two peak temperatures between 50 and 60 °C occurred at 8–12th hour and 50–65th hour, respectively. Operating parameters that converted the most volatile solids and carbons in the feedstock were as follows: 1.6 l air/kg dry solid-min of air suction rate, 32% of seeding and 50% of agitation time.

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1. Introduction

In recent years, several small-to-medium sized in-vessel composting systems for on-site application have been developed and used by schools, restaurants, and hotels. The dimensions of those systems and space requirements are usually large, and times for maturity are from 14 days to a month (Regenstein et al., 1999; Clark, 2000; Vossen et al., 2000; ORDEQ, 2002). A faster and more efficient system is desired.

Ideal composting conditions are the carbon to nitrogen ratio of the composting material between 20 and 40, the moisture content between 50% and 65%, adequate oxygen supply, small particle sizes, and enough void space for air to flow through. Those conditions have been well known for a long time, but only the first three conditions have been considered in previous studies. Less time for maturity would be achieved if operating parameters that govern the aerobic biodegradation were thoroughly studied and optimized.

This study is a part of a comprehensive effort to develop a more fundamental engineering approach to food waste composting. To minimize the effect of particle sizes and to improve the mass transfer between air and solids, the waste was ground into powder. Rice husks were used as the bulking agent for the adjustment of the carbon-to-nitrogen ratio and the moisture content. Composts from preliminary experiments were used as the seeding material. A laboratory reactor was designed to improve the air–solid contact and solid mixing. The effects of operating parameters such as air suction rate, the percentage of seeding and the time fraction of agitation on the biodegradation of food waste during thermophilic composting were studied. The results and the conclusion drawn in this study will be applied for better designs in the future.

2. Methods

2.1. Composting material and bulking agent

The uniformity of a synthetic food waste offers a distinct advantage over restaurant or cafeteria wastes in
controlling the variability of substrate characteristics (Clark et al., 1977; Schwab et al., 1994). To control the variability of substrate characteristics, a synthetic food waste made of homogeneous dog food pellets with a balanced composition of important nutrients for degradation similar to those used in composting studies of Nakasaki and Ohtaki (2002), Nakasaki et al. (2004) was used in this study. The approximate chemical formula of the dog food selected was C_{16}H_{27}O_{9}N, which was similar to C_{16}H_{27}O_{9}N of the average kitchen waste in Taiwan (Table 1). The mixture of ground dog food particles and water was a paste material similar to grinded kitchen or cafeteria wastes.

2.4 kilograms of dry dog food pellets were first ground to powder and mixed with rice husks and different percentages of compost products used as seeding to form 10 kg of the composting material (feedstock). The percentage of seeding was defined to be the amount of dry seeding material in 10 kg of total dry feedstock. 16% of seeding meant that the dry composting material contained 1.6 kg of compost product, 6 kg of rice husk and 2.4 kg of dog food. Water was then added to make a composting material of 55% moisture content. Physical and chemical properties of typical kitchen wastes in Taiwan, raw materials, feedstock, and the final compost product are presented in Table 1.

### 2.2. Experimental apparatus

A specially designed laboratory-scale reactor (Fig. 1) was used in this study. The reactor system consisted of an insulated cylindrical vessel made of stainless steel, a variable-speed induced fan, a condenser, an oxygen analyzer, and a carbon dioxide analyzer. A vertical ribbon mixer/agitator driven by a high-torque, low-speed electric motor operated intermittently was installed in the reactor for mixing composting materials.

### 2.3. Physico-chemical monitoring and analyses

CO$_2$ and O$_2$ concentrations in the reactor outlet gas were continuously measured by a CO$_2$ analyzer (ABB EasyLiner IR) and an O$_2$ analyzer (ABB Magneto-mechanical analyzer) placed after the induced fan. Temperatures at different heights in the reactor were continuously measured by thermocouples connected to temperature recorders. An IBM PC was used for continuous data acquisition and storage. Solid samples were taken every 8 h. Important physico-chemical parameters of the samples such as the pH value, moisture, volatile matter (VM), ash, total nitrogen, total organic carbon were analyzed according to the standard methods [American Public Health Association American Public Health Association (APHA) et al. (1992)]. All compost products at the end of the experiments were tested for maturity based on the indices such as the ratio of carbon to nitrogen of water extractable liquid (C$_{OW}$/N$_{OW}$) proposed by Chanyasak et al. (1982), and the ratio of...
carbon in water extractable liquid to total nitrogen of \((\text{C}_{\text{OW}}/\text{N}_{\text{OT}})\) proposed by Hue and Liu (1995), and Bernal et al. (1998). Seed germination test was also conducted.

2.4. Data analysis

The air suction rate, the percentage of seeding and the time fraction of agitation were selected as influencing parameters (independent variables), and the percentage of the total volatile solid loss (TVS) and the carbon conversion (%) were corresponding parameters (dependent variables). The effects of independent variables on the dependent variables were analyzed as a quadratic function:

\[
P_i = a_0 + a_1X + a_2Y + a_3Z + a_{11}X^2 + a_{22}Y^2 + a_{33}Z^2 + a_{12}XY + a_{13}YZ + a_{23}XZ
\]  

(1)

where \(P_i\) is the predicted response (dependent variables) such as the percentage of TVS loss (%) or the carbon conversion (%); \(X\), \(Y\) and \(Z\) are independent variables (percentage of seeding, air suction rate and time fraction of agitation); \(a_0\) is the offset term; \(a_1\), \(a_2\), and \(a_3\) are linear coefficients; \(a_{11}\), \(a_{22}\), \(a_{33}\) are squared terms; and \(a_{12}\), \(a_{23}\), \(a_{13}\) are interaction coefficients.

Best values of \(P_i\) in Eq. (1) were nonlinearly evaluated using the Newtonian method of the “Solver” function in Microsoft Excel v. 5.0. Up to 100 iterations were used to converge the errors of sum of the squares (SSE) between the experimental and estimated values to a minimum value. The initial values of parameters were estimated using a built-in visual procedure based on a limited fit algorithm (Wen et al., 1994). The Windows software Statistica was employed for multivariate analysis to obtain best values of coefficients in Eq. (1). The response surface contour plots were constructed using Igor Pro v. 3. The statistical diagnosis of the above parameters was based on the approach reported by Wen et al. (1994).

3. Results and discussion

3.1. Selection of operating conditions of thermophilic composting

Prior to conducting optimization studies, several preliminary experiments were carried out to identify proper ranges of operating parameters. When the air suction rate was less than 0.5 l per kilogram of dry solids per minute (l/kg DS-min), the oxygen concentration in the exhaust gas was below 5% at peak temperature. Obnoxious odors were also smelled. A higher air suction rate supplied more oxygen to the system and produced more CO\(_2\), but it also cooled the bed. When the air suction rate was over 2.5 l/kg DS-min, the cooling effect became so important that the temperature was lower than 45 °C in the first day. It took longer for the temperature to reach 55 °C or above. The proper range of air suction rate was between 0.8 and 2.0 l/kg DS-min. Three percentages of the seeding (0%, 16% and 32%) were selected.

Agitation facilitated solid mixing and air-solid contact. Without agitation, the material at the bottom of the reactor became more packed and was flooded with water after 24 h. More frequent agitation improved performance and resulted in more uniform temperature distribution. When the agitator operated more than 50% of the time, no improvement was observed. The range was thus selected between 10% and 50%.

3.2. Profiles of temperature and carbon dioxide evolution

Fig. 2(a)–(c) showed the variations of the temperature, the pH value, CO\(_2\) evolution and O\(_2\) utilization rates, the percentage of TVS loss, and the carbon conversion with time recorded during a typical self-heating composting of synthetic food wastes. The air suction rate was set at 1.2 l/kg DS-min and the motor that drove the agitator/mixer operated for 50% of the time every 10 min (time fraction of agitation = 0.5). Two major temperature peaks (about 50 and 61 °C) along with O\(_2\) utilization and CO\(_2\) evolution rates were observed at 10th and 50th hour, respectively. This implied that two major stages of composting caused by two groups of microorganisms were involved. A minor peak temperature of 35 °C at 80th hour was also observed in this case, but it was not apparent in many other cases.

CO\(_2\) evolution and O\(_2\) utilization rates were found to be linearly dependent of the bed temperature (Fig. 3):

\[
\text{W}_{\text{CO}_2} = 0.523T - 15.52 \quad (r^2 = 0.962)
\]  

(2)

\[
\text{W}_{\text{O}_2} = 0.353T - 10.06 \quad (r^2 = 0.953)
\]  

(3)

where \(W_{\text{CO}_2}\) and \(W_{\text{O}_2}\) were hourly CO\(_2\) evolution rate (g/kg VS-h) and O\(_2\) utilization rate (g/kg VS-h), respectively; \(T\) was the temperature (°C) between 30 and 65 °C. This is in agreement with the general understanding that aerobic composting, an exothermic process, causes the temperature of a well-insulated system to rise as the composting process proceeds (Haug, 1993; Richard, 1997). Higher temperature results in acceleration in the composting process, reflecting increases in microbial growth rates, and the reaction rate. This linear relationship also reflected that the bed was well agitated and well circulated with air. Little heat was accumulated in the bed once the aerobic biodegradation was over. The bed temperature was actually a consequence caused by the aerobic biodegradation and was better expressed in term of CO\(_2\) evolution or O\(_2\) utilization rates. The linear relationship is quite different from the quadratic
relationship reported by Haug (1993) and Regan et al. (1973), or the exponential relationship by Schultze (1962) and Wiley and Pearce (1957). The peak CO₂ evolution and O₂ utilization rates were 50% higher than those reported by other researchers (Table 2).

During the first stage of composting, the composting material hydrolyzed very rapidly and the pH value dropped steadily from 6.5 to 5.0. At the end of the first temperature cycle (at 30th hour), the pH value was at its minimum. This point could be considered as the point that separated the two composting stages. The pH value rose with the temperature in the second stage, which indicated that the rate of aerobic biodegradation was faster than that of hydrolysis. The pH continued to rise to 9 after 60 h and stayed unchanged until the end.

In the beginning of the composting process, mesophilic bacteria mainly contributed to the temperature rise and the evolution of CO₂. As the temperature rose to 40 °C or above, thermophilic bacteria took over as the leading group of bacteria. In the third stage of composting, mesophilic bacteria became active again.

The percentages of TVS loss and carbon conversion at the end of 96 h were 29% and 24%, respectively (Fig. 2(c)). Both curves were a combination of two S-shaped curves as shown in Fig. 2(c).

The ratio of carbon-to-nitrogen of water extractable liquid (C<sub>OW</sub>/N<sub>OW</sub>) continued to decrease from an initial value of 29 during the composting process and reached a final value of 4.5 at the end of 96 h. This value was close to 5–6 proposed by Chanyasak et al. (1982), Jimenez and Garcia (1992) as a maturity index for compost prepared with different materials. The ratio of organic carbon in water extractable liquid to the total nitrogen in the solid (C<sub>OW</sub>/N<sub>OT</sub>) was 0.64, which was in the range of 0.55 and 0.7 as a maturity index proposed by Hue and Liu (1995), Bernal et al. (1998). The final compost product also passed the seed germination test.
The onset of temperature rise in the first stage of composting was almost independent of the process conditions. The temperature began to rise at the 4–5th hour and reached its maximum between 10th and 12th hour as shown in Fig. 2(a). In the second stage, the peak time and the CO2 evolution rate changed with process conditions. Except in the cases with 32% of seeding, the profiles of temperature and CO2 evolution rate showed two distinct composting maximums as shown in Fig. 2.

When more seeding material was present, the location of the second CO2 peak appeared at an earlier time (Fig. 4). When the percentage of the seeding reached 32% (seeding to waste ratio = 1.33), the second peak moved even further and the profile became a broad composite of many peaks and the temperature of the first peak was over 60°C (Fig. 5). No clear separation of the stages was observed. This was similar to that reported by Nakasaki et al. (1985) in their study of the change in microbial numbers during thermophilic composting of sewage sludge at 60°C. The final products of all experiments at the end also passed the maturity tests as suggested by many authors (Table 3).

### 3.3. Derivation of empirical models

To derive an empirical model, air suction rate, the percentage of seeding, and the time fraction of agitation were selected as independent variables, and TVS loss and carbon conversion were selected as dependent variables.

By performing nonlinear regression analyses of experimental data listed in Table 4, the following equations were generated:
where \( P_1 \) and \( P_2 \) were TVS loss (%) and the carbon conversion (%), respectively; \( X, Y \) and \( Z \) are the percentage of seeding, air suction rate and the time fraction of agitation, respectively; \( r^2 \) is the determination of regression; \( F \) is the regression test statistic.

A regression model is considered to be statistically significant if the calculated regression test statistic, the \( F \) value, is larger than the value of \( F(l, m, a) \) in the \( F \) distribution at a probability of \( a \) (Box et al., 1978), where \( l \) is the number of coefficients (parameters) less 1, \( m \) is the degree of freedom, and \( a \) is a probability level. The degree of freedom is defined to be the number of data less the number of coefficients. There are 18 sets of data and 10 coefficients \((a_0, a_1, a_2, a_3, a_11, a_12, a_22, a_13, a_23, \) and \( a_{33} \)) needed to be evaluated by regression analysis in either Eq. (4) or Eq. (5). \( \mu \) is therefore equal to 9 and \( \nu \) is equal to 8. The calculated \( F \) values of 18.23 and 4.55 are larger than the \( F(9, 8, 0.05) \) value of 3.39 at a 95% confidence level (\( a = 0.05 \)) with 10 parameters (\( \mu = 9 \)) and 8 degrees of freedom (\( \nu = 8 \)). The calculated \( r^2 \) values of 0.95 and 0.84 also indicate that the two regression models are in fair agreement with experimental data.

### 3.4. Effects of process variables on TVS loss

To examine the dependence of the loss of total volatile solids on the three influencing parameters, it was convenient to fix one parameter and to construct the contour plots using the other two parameters. The agitation was the least important parameter to our past experience and was first set at a constant value of 0.5. The contours of TVS loss (%) versus the air rate and the percentage of seeding (%) were then constructed. As shown in Fig. 6(a), more volatile solids were converted into carbon dioxide, water and ammonia, as more seeding material was added into the initial feedstock. The loss of TVS was highest when the percentage of seeding was 32%. The optimal air suction rate was between 1.2 and 1.6 l/kg DS-min depending on the percentage of seeding. The air suction rate that gave the highest TVS loss shifted from 1.3 to 1.5 l/kg DS-min when the seeding
material in the initial feedstock was increased from 0% to 32%.

As shown in Fig. 6(b) in which the percentage of seeding was fixed at 16%, the response surface has a “saddle” shape. The TVS loss reached a maximum value of 20.4% at an air suction rate of 1.66 l/kg DS-min, when the time fraction of agitation was 0.2. More agitation facilitated better solid mixing and air–solid contact, speeded up the composting process, and converted more volatile solids. When the time fraction of agitation was 0.5, there was a maximum value TVS loss at the air suction rate of 1.45 l/kg DS-min. More frequent agitation also consumed more energy and nutrients; thus, it was less economical if the final products would be used as the organic fertilizers or soil conditioners. The desired time fraction of agitation was between 0.1 and 0.2. Same conclusions could be drawn from the contour plots of the carbon conversion model, which were similar to those of TVS loss.

4. Conclusions

Principal conclusions derived from this investigation are summarized as follows:

1. Synthetic food wastes made of dog food could be composted successfully in 4 days. All products at the end of a 4-day composting period passed all maturity tests.
2. In most cases except those of 32% of seeding, the process involved two major distinct stages of composting. The peaks of temperature, CO$_2$ evolution and O$_2$ utilization rates occurred in the ranges of 8–12 h and 50–65 h. The peak temperature of the first stage was between 48 and 52°C, and the peak temperature of the second stage was between 55 and 62°C. The CO$_2$ evolution and O$_2$ utilization rates were linearly dependent of temperature.
3. At any level of seeding between 0% and 32%, the TVS loss was highest when the air suction rate was between 1.2 and 1.6 l/kg DS-min. Frequent agitation accelerated the process and converted more volatile solids.

Future work will be focused on the development of a practical in-vessel composter based on the experience gained in this work, the bacteria population and their activities at different composting stages.

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