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Co-composting of green waste and food waste at low C/N ratio

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ABSTRACT

In this study, co-composting of food waste and green waste at low initial carbon to nitrogen (C/N) ratios was investigated using an in-vessel lab-scale composting reactor. The central composite design (CCD) and response surface method (RSM) were applied to obtain the optimal operating conditions over a range of preselected moisture contents (45–75%) and C/N ratios (13.9–19.6). The results indicate that the optimal moisture content for co-composting of food waste and green waste is 60%, and the substrate at a C/N ratio of 19.6 can be decomposed effectively to reduce 33% of total volatile solids (TVS) in 12 days. The TVS reduction can be modeled by using a second-order equation with a good fit. In addition, the compost passes the standard germination index of white radish seed indicating that it can be used as soil amendment.

1. Introduction

Food waste (i.e. cooking wastes and food residuals) and green waste (i.e. pruning yard wastes and fallen leaves) are the major organic municipal solid wastes in Taiwan. Food waste makes up 18–20% and green waste 22–30% of the total municipal solid waste by weight (Taiwan EPA Statistics, 2006). Composting, which biologically decomposes and stabilizes organic substances under thermophilic conditions as a result of biologically produced heat (Barrington et al., 2003; Iyengar and Bhave, 2006), is a proven method for treatment of green waste and food waste (Lemus and Lau, 2002; Nakasaki and Ohtaki, 2002). However, the waste physical/chemical properties may not always be suitable for composting. For example, high moisture content in food waste or low nitrogen content of green waste may result in long treatment time or low degradation efficiency. Co-composting of two or more types of organic materials is expected to overcome the disadvantages of composting a single material.

The carbon to nitrogen (C/N) ratio is one of the important factors affecting the composting process as well as the properties of the end product (Zhu, 2007; Chang and Hsu, 2008). A C/N ratio between 25 and 30 is usually considered as the optimum ratio for composting. However, recent studies have shown that composting can be carried out effectively at a lower C/N of 15 (Huang et al., 2004; Zhu, 2007). Composting at low C/N ratios will reduce the requirement of bulking agent for adjusting the initial C/N ratio of a food waste composting mixture.

Moisture content of the composting mixture is an important factor as it provides a medium for the transport of dissolved nutrients required for the metabolic and physiological activities of microorganisms. Several researchers report that the optimal moisture content for composting/co-composting at high C/N ratios (>20) is around 55–60% (Tiquia et al., 1996; Liang et al., 2003). However, no study has been designed to address the interaction between moisture content and C/N ratio for co-composting of wastes at low C/N ratios.

Consequently, the objective of this study is to investigate the effects of low C/N ratio and moisture content on the co-composting of green waste and food waste. Experiments were carried out in an in-vessel, lab-scale composting system. The central composite design (CCD) and response surface technology (RSM) were applied to obtain optimal conditions for co-composting of green waste and food waste.

2. Materials and methods

2.1. Feedstocks

All food wastes were collected on five consecutive days from the same restaurant that served rice, noodles, vegetables, meats and seafood. The green waste, mainly raked leaves and grass clippings, was collected from National Chiao Tung University, Hsinchu City, Taiwan. The seeding material was collected from a commercial composting plant in Hsinchu City. Rice husk from the Hsinchu Farmers' Association was selected as the bulking agent. The characteristics of the feedstocks are shown in Table 1.

2.2. Composting reactor

The schematic diagram of the composting reactor is shown in Fig. 1. A 120-L stainless steel cylindrical reactor (60 cm length

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Table 1
Characteristics of feedstocks.

Parameter	Food waste	Green waste	Rice husk
Moisture content (%)	70–80	7–15	8–11
pH	3.8–6.5	5.8–6.6	7.1–7.3
C (%)	47.35	41.76	41.66
N (%)	5.35	0.8	1.22
H (%)	7.31	5.76	5.22
C/N	8.85	52.4	34.17

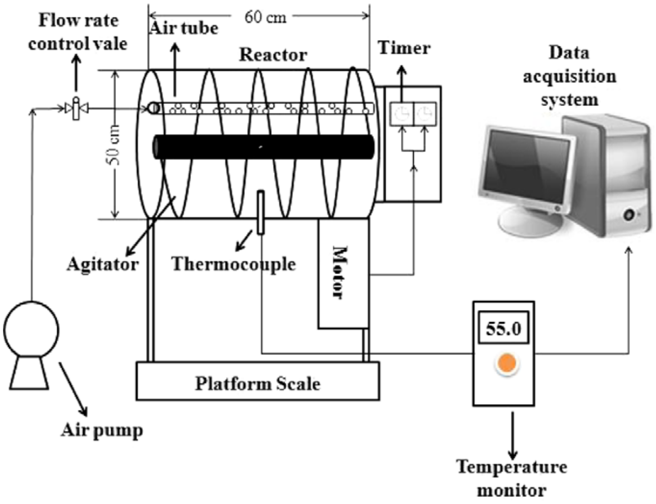

Fig. 1. Schematic diagram of in-vessel lab-scale composting reactor.

and 50 cm diameter) with insulation was used for the composting study. A spiral-leaf agitator along with a timer was mounted inside the reactor to mix the feeding materials uniformly. In addition, an aeration tube was installed at the bottom of the composting reactor to maintain an aerobic condition; the air was supplied using an air pump at a rate of 10 L/min. A thermocouple was placed at the bottom of the reactor to monitor the reactor temperature continuously using a PC based data acquisition system.

2.3. Composting experiments

Food and green wastes are non-homogeneous even after extensive natural mixing due to their larger particle sizes. Therefore, the wastes were ground up using either food processor or shattered with a pestle to around 5 mm particles; they were mixed before composting to assure that the mixture was homogeneous. The mixture's C/N ratio was calculated based on the weight percentages of the component wastes in the mixture excluding the 2-kg seeding materials. The moisture content of the feedstocks was analyzed prior to each experimental run. The difference between required and available moisture contents was adjusted by sprinkling tap water on the surface of the composting mixture and mixing the content thoroughly. Other physical/chemical factors were measured throughout the composting period. In addition, germination tests and heavy metal analyses were carried out for examining the quality of the composted product.

2.4. Experimental design

The CCD was applied for selecting moisture contents and C/N ratios in order to assure experimental quality and decrease the total number of experiments. This design enables the construction of second order polynomials to be related to one dependent and two independent variables. The total number of experiments (N) required for two independent variables was determined using Eq. (1) (Akhnazarova and Kafarov, 1982).

$$N = 2^K + 2K + n_c \tag{1}$$

where K represents the number of independent variables ($K = 2$ in this study), and n_c is the center point. Predetermined ranges of independent variables, i.e. MC (45–75%) and C/N ratio (13.9–19.6), were used for CCD and the data were analyzed using Minitab® 14.1 Statistical software. Three replications of the center point were selected for CCD and 11 composting experiments were analysed (Table 2). Subsequently, the optimal operating conditions were obtained by using the response surface method.

2.5. Analytical measurements

Laboratory analyses included measurements of moisture content, pH, temperature, volatile solids, water soluble total organic carbon (TOC_W), and water soluble total Kjeldahl nitrogen (TKN_W). Samples of about 200 g were collected every 12 h and dried in an oven at 105 °C for 24 h; the loss of weight was taken as the moisture content. The oven-dried sample was further heated at 550 °C for 4 h for the determination of volatile solids. For measuring the compost pH, raw samples were mixed with deionized water at a weight ratio of 1:10. The mixture was shaken for 1 h and then allowed to settle under quiescent conditions; pH of the clear supernatant was measured in the top clear liquid with a pH meter.

TOC_W and TKN_W were measured using a TOC analyzer (OI Analytical model 1010) and a TKN analyzer (Gerhardt Vap 50), respec-

Table 2
Experimental design of lab-scale composting.

Run order	Wt. of feedstocks on dry basis (kg)			Carbon content of mix (C, %)	Experimental condition		Final pH	Highest temperature (°C)	Time to reach 55 °C (h)	Time above 55 °C (h)	TVS reduction (%)
	Green waste	Food waste	Rice husk		MC (%)	C/N					
1	4.55	2.95	2.5	43.38	60	19.6	8.97	67.5	29.0	27.0	32.8
2	3.4	4.1	2.5	44.03	60	16.2	8.83	75.2	18.4	46.9	31.4
3	2.25	5.25	2.5	44.67	60	13.9	8.82	73.3	20.5	28.7	31.0
4	3.4	4.1	2.5	44.03	45	16.2	8.84	71.1	34.8	28.7	17.9
5	4.21	3.29	2.5	43.57	70.61	18.5	8.9	53.4	77.0	0	28.6
6	3.4	4.1	2.5	44.03	60	16.2	8.81	72.5	20.5	59.5	31.3
7	3.4	4.1	2.5	44.03	75	16.2	6.47	44.9	*	0	14.8
8	4.21	3.29	2.5	43.57	49.39	18.5	8.86	65.4	31.2	41.6	23.2
9	2.59	4.91	2.5	44.48	70.61	14.5	3.88	35	*	0	15.9
10	3.4	4.1	2.5	44.03	60	16.2	8.91	75.2	33.8	65.6	31.6
11	2.59	4.91	2.5	44.48	49.39	14.5	8.83	69.4	20.4	42.8	31.6

Note: Two kilograms of homogeneous compost were added as seed in all runs; MC represents moisture content; * Thermophilic phase not reached at all.

tively, on samples that had been centrifuged at 2000 rpm for 20 min and filtered through a 0.45 μm filter paper. The germination test was performed for 48 h at 25 °C in the dark with 20 radish seeds placed on a 9 mm filter paper (Whatman #1) soaked with 4 mL of compost extract (Bertran et al., 2004), and placed in a Petri dish. Moreover, the germination test was repeated with deionized water as a control, and extract of commercial compost. The following equations were used to calculate the relative seed germination (Eq. (2)), relative root growth (Eq. (3)), and germination index (GI) (Eq. (4)) (Tiquia et al., 1996; Zucconi et al., 1981).

$$\text{Relative seed germination}(\%) = \frac{\text{Number of seeds germinated in compost extract}}{\text{Number of seeds germinated in control}} \times 100 \qquad (2)$$

$$\text{Relative root growth}(\%) = \frac{\text{Mean root length in compost extract}}{\sqrt{\text{Mean root length in control}}} \times 100 \qquad (3)$$

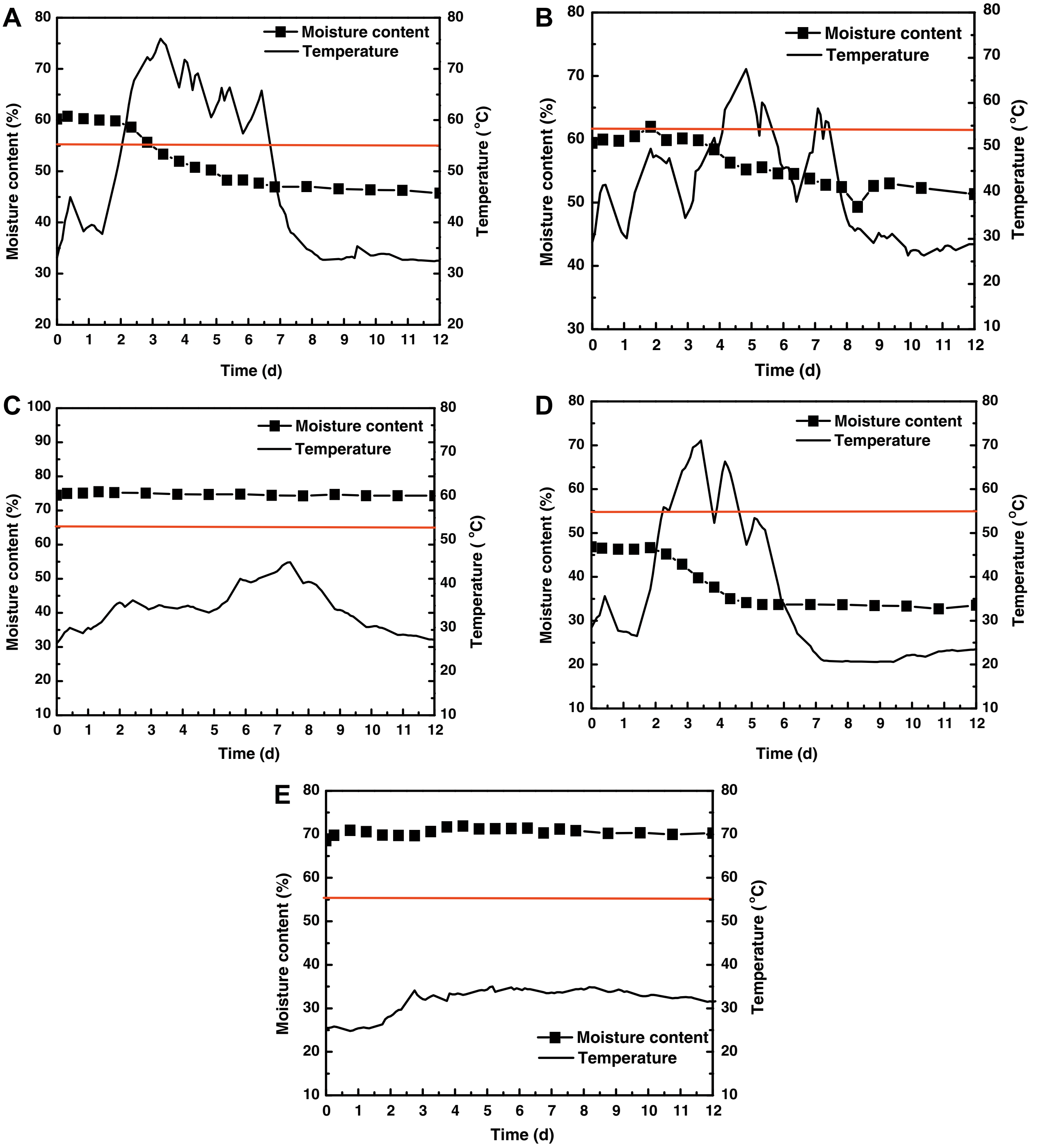

Fig. 2. Profiles of moisture content (MC) and temperature during composting: (A) MC 60% and C/N 16.2; (B) MC 60% and C/N 19.6; (C) MC 75% and C/N 16.2; (D) MC 45% and C/N 16.2; and (E) MC 70.61% and C/N 14.5.

$$\mathrm{GI}(\%) = \frac{(\text{Relative seed germination}) \times (\text{Relative root growth})}{100} \tag{4}$$

3. Results and discussion

3.1. Effects of moisture content and C/N on composting

Table 2 summarizes the results of the composting experiments. The moisture content affects the microbial activity directly, the compost temperature, and hence the rate of decomposition. Fig. 2A and B show the variation of moisture content during the composting period under the conditions of the same initial moisture content (60%) with two different C/N ratios, i.e. 16.2 and 19.6. Fig. 2C and D show the composting performance with respect to temperature under extreme initial moisture content conditions (75% and 45%) while maintaining the initial C/N at 16.2. There is no significant change in moisture content in Fig. 2C during the composting period at higher initial moisture content levels. Under this condition, it appears that oxygen transfer limited microbial activity thus resulting in a slow temperature increase in the system. The temperature shown in Fig. 2D rises to above 65 °C in 3 days thus decreases the moisture content. This high temperature is not maintained for a long time; the temperature even decreases sharply when the moisture content is reduced to 35%. Liang et al. (2003) observed a consistently lower microbial activity even at a controlled high temperature of 57 °C for an aerobic composting with

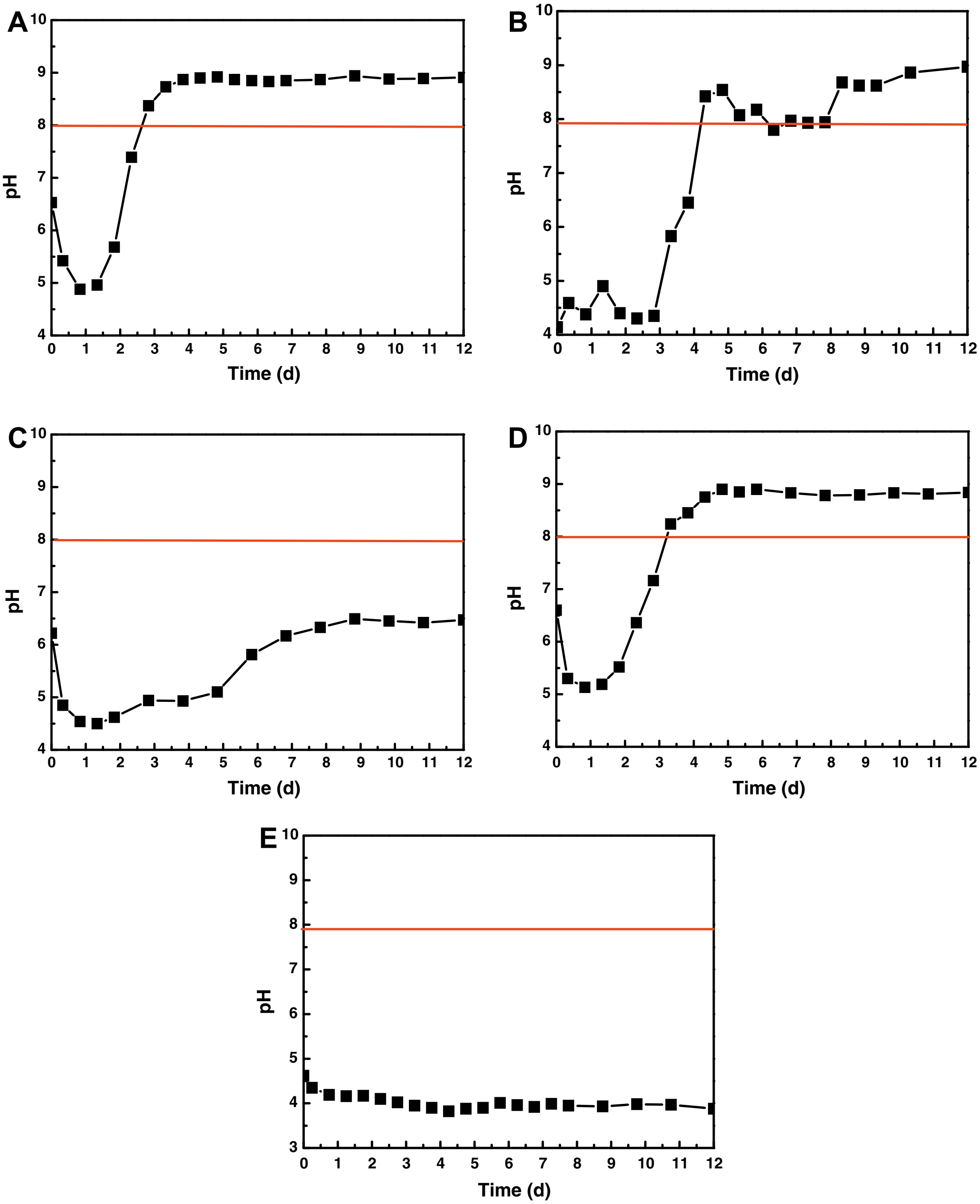

Fig. 3. Profiles of pH during composting: (A) MC 60% and C/N 16.2; (B) MC 60% and C/N 19.6; (C) MC 75% and C/N 16.2; (D) MC 45% and C/N 16.2; and (E) MC 70.61% and C/N 14.5.

a relatively lower moisture content range of 30–40%. Fig. 2E, which appears to have a similar profile as Fig. 2C, shows the composting results at a high moisture content (70.61%) and low C/N ratio (14.5). Under these conditions, the composting moisture content barely varies but the temperature is not satisfactory.

Fig. 3 shows pH changes during composting. In a number of experiments, the pH of the system reduced from 6 or so to 4 or 5 during the initial stage of composting, which is likely due to the production of organic acids. Bech-friis et al. (2001) indicated that the decomposition of organic acids was followed by a rapid increase of pH caused by the transformation of organic nitrogen into ammonium nitrogen. Thereafter, the pH generally increased sharply to 8 or 9. The variation of pH at 60% moisture content and 19.6 C/N ratio (Fig. 3B) is similar to that at 60% moisture content and 16.2 C/N ratio (Fig. 3A), and the system pH at the end of the process reaches around 9. Zhu (2007) observed a similar pH value at the end of an aerobic composting.

Changes in TOC$_W$ and TKN$_W$ concentrations during composting represent the decomposition of organic matter and nitrogen transformation, respectively. At 60% moisture, variations of TOC$_W$ concentration for C/N ratios of 16.2 and 19.6 are shown in Fig. 4A and B, respectively. The hydrolysis of solid organic matter to water soluble organic matter by microorganisms can explain the slight increase in the TOC$_W$ concentration during the initial stage of composting. Thereafter, the TOC$_W$ concentration decreases sharply when the temperature reaches the thermophilic level. Fig. 4C and D show the variation of TOC$_W$ concentration at high moisture contents of 75% and 70.61%, respectively. The difference between the high TOC$_W$ concentrations here may have been caused by a higher initial protein availability in the food waste collected for conducting experimental run 7 (Fig. 4C and D). At the initial stage of composting, increases in the TKN$_W$ concentrations are observed at 60% and 75% moisture contents (Fig. 4A–C). However, the concentrations decreased considerably, presumably due to the mineralization of proteins, amino acids and peptides, and either ammonia volatilization or the transformation of NH_4^+—N into nitrate by nitrifying bacteria at matrix temperature below 40 °C. On the other hand, no change in TKN$_W$ concentration was observed at lower moisture content of 45% and C/N ratio of 16.2 (Fig. 4D).

The total volatile solids (TVS) represent the biodegradable organic matter; the decomposition of organic matter is indicated by the difference between the initial and final system TVS (Kwon and Lee, 2004). Fig. 5A and B show the TVS reduction ratio at 60% moisture for C/N ratios of 16.2 and 19.6, respectively. The TVS reduction percentage is greater than 30% at the end of the composting period of 12 days for both C/N ratios. Fig. 5C and D show poor TVS reduction under the conditions of same initial C/N ratio (16.2) with 75% and 45% moisture contents, respectively. The profile of TVS reduction ratio at 70.61% moisture content and 14.5 C/N ratio (Fig. 5E) is similar to that at 75% moisture content and 16.2 C/N ratio (Fig. 5C). Although some runs exhibited poor composting, roughly 15% of TVS was still lost.

From Table 2, the compost moisture content and its interaction with C/N ratio have a strong influence on the TVS reduction ratio. The response surface and contour plots of the experimental data prepared using Minitab®14.1 are shown in Fig. 6A and B, respec-

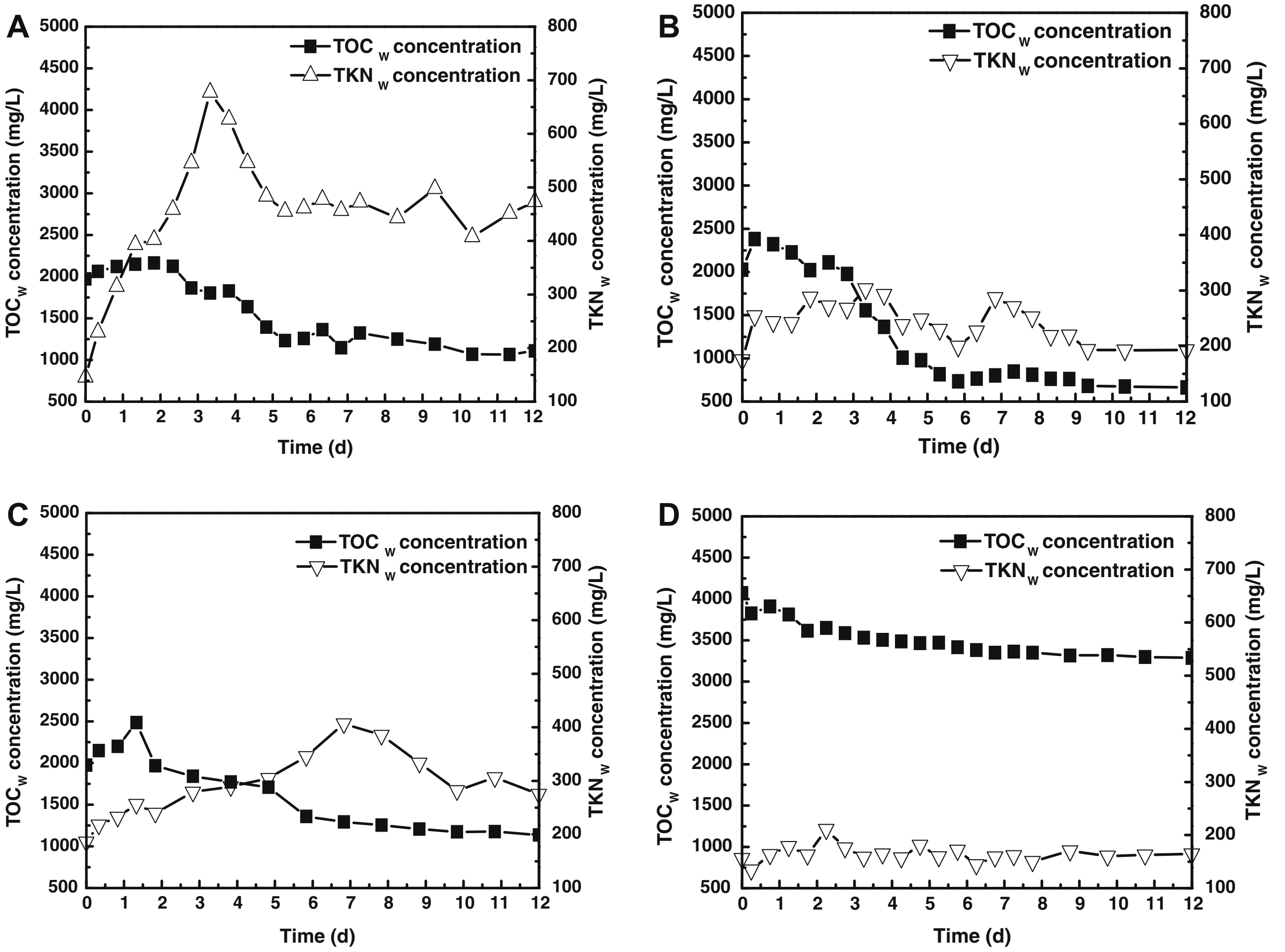

Fig. 4. Profiles of TOC$_W$ and TKN$_W$ concentrations during composting: (A) MC 60% and C/N 16.2; (B) MC 60% and C/N 19.6; (C) MC 75% and C/N 16.2; and (D) MC 45% and C/N 16.2.

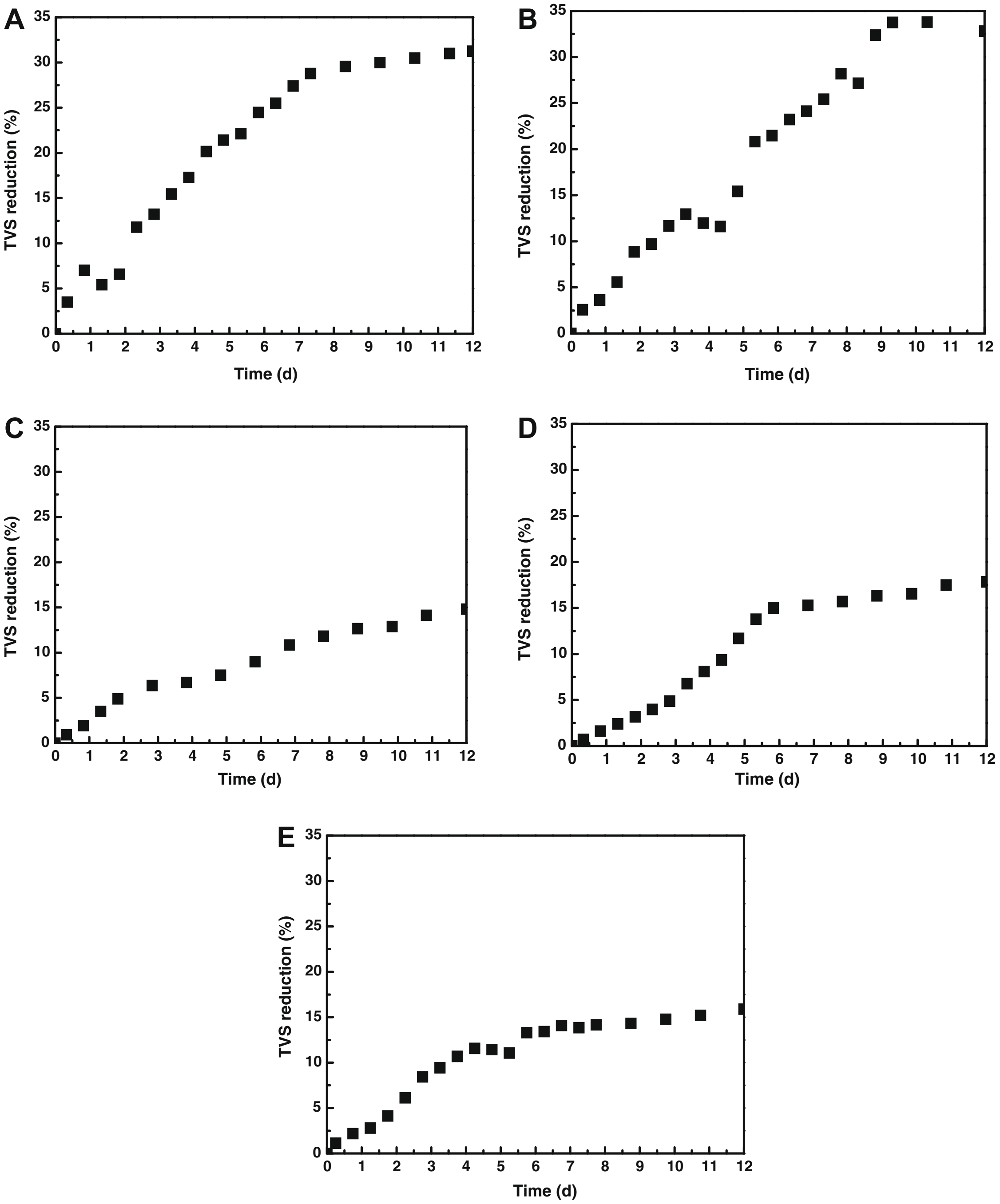

Fig. 5. Profiles of TVS reduction ratio during composting: (A) MC 60% and C/N 16.2; (B) MC 60% and C/N 19.6; (C) MC 75% and C/N 16.2; (D) MC 45% and C/N 16.2; and (E) MC 70.61% and C/N 14.5.

tively. Both figures reveal that the maximum TVS reduction ratio occurs at a moisture content of around 60% and a C/N ratio of 19.6. Fig. 6B indicates that the TVS reduction ratio is at its maximum under the conditions of low moisture contents and high C/N ratios, or high moisture contents and low C/N ratios. Therefore, the interaction between C/N ratio and moisture content affects TVS reduction, presumably because of the impact on oxygen transport and microbial activity.

3.2. Modelling the optimum co-composting conditions of green waste and food waste

The analysis of variance (ANOVA), calculated using Minitab®14.1 for TVS reduction, is shown in Table 3. The *P*-values obtained from ANOVA in Table 3 are smaller than 0.05 indicating that the result of the TVS reduction ratio can be fitted well by a second-order response surface plot. The second-order model for the central composite design (CCD) experimental design is shown in Eq. (5) and Table 4.

$$Y = 87.3064 + 3.5118X_1 - 10.6337X_2 - 0.0658X_1^2 + 0.0407X_2^2 + 0.1403X_1X_2 \qquad (5)$$

where Y is the TVS reduction (%), and X_1 and X_2 are moisture content (%) and C/N ratio, respectively. Minitab®14.1 is also used to calculate residuals versus fitted values for testing the accuracy of Eq. (5). The fitted values of the residuals should be shapeless and not related to other variables if the model is correct and the hypotheses

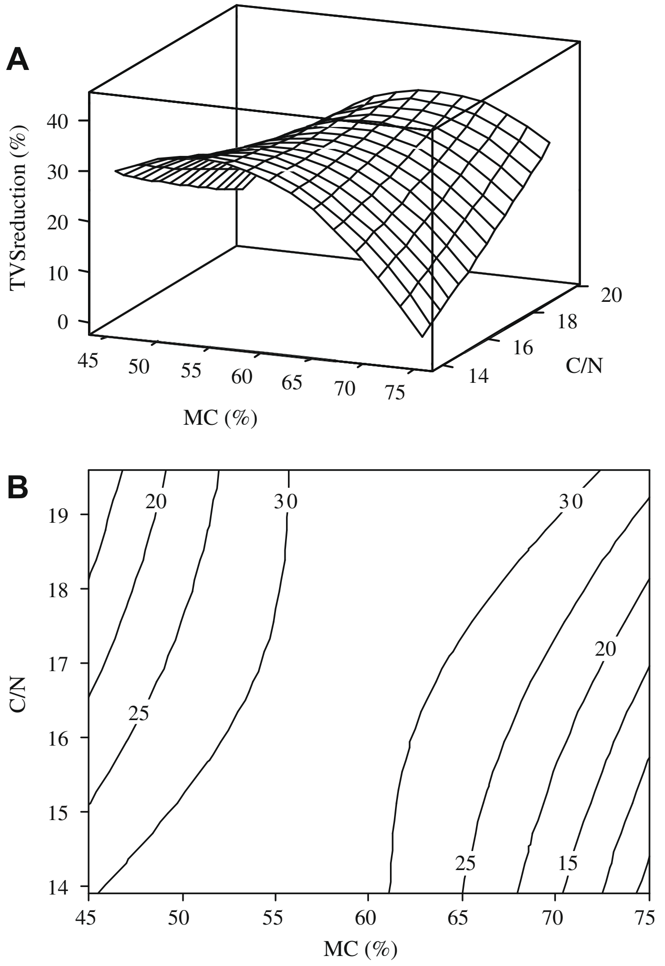

Fig. 6. (A) Response surface and (B) contour plot of TVS reduction ratio.

Table 3
Analysis of Variance for TVS (total volatile solids) reduction ratio.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	496.78	496.78	99.36	84.20	0.00
Linear	2	32.09	32.09	16.05	13.60	0.01
Square	2	353.91	353.91	176.96	149.96	0.00
Interaction	1	110.78	110.78	110.78	93.87	0.00
Residual error	5	5.90	5.90	1.18		
Lack-of-fit	3	5.82	5.82	1.94	46.01	0.02
Pure error	2	0.08	0.08	0.04		
Total	10	502.68				

Table 4
Estimated regression coefficients for TVS (total volatile solids) reduction ratio.

Term	Coeff.	SE coeff.	T	P
Constant	87.31	0.63	50.09	0.00
Moisture content (MC)	3.51	0.38	−4.77	0.01
C/N	−10.63	0.38	2.11	0.09
MC ∗ MC	−0.07	0.46	−16.19	0.00
C/N ∗ C/N	0.04	0.46	1.11	0.32
MC ∗ C/N	0.14	0.54	9.69	0.00
	R^2 = 98.8%		R^2 (adj) = 97.7%	

Table 5
Outcomes of germination test.

Item/parameter	Control test	Compost extract of in-vessel lab-scale reactor	Compost extract of commercial compost
Total seeds	400	400	400
Germinated seeds	397	394	202
Mean root length (cm)	2.93	0.84	0.28
Relative seed germination (%)	–	99.2	50.9
Relative root growth (%)	–	49.1	16.4
Germination index (%)	–	48.7	8.3

Table 6
Comparison of heavy metal concentrations observed in composts obtained from in-vessel lab-scale composting reactor.

Country	Metal concentration limitation (mg/kg on dry basis)					
	Cu	Cr	Zn	Pb	Cd	Ni
Taiwan, ROC	150	150	500	150	5	25
USA	150	1500	600	150	20	210
European Union	50–140	100–150	150–300	50–300	1–3	30–75
Belgium	750	500	2500	600	12	100
Netherlands	190	380	720	530	12	210
Japan	125	500	150	400	5	100
Germany	200	500	600	1000	5	200
Present study	44.4	73.5	278.8	30.8	N.D.	62.0

are true. The plot of residuals versus fitted values for the TVS reduction ratio does not show any abnormal construction such as a funnel or bell shape. The normal probability plot is used to test the normality of error distribution. For the experimental data, a linear normal probability plot is observed demonstrating that the error distribution is normal and the experimental data conforms to normal distribution.

3.3. Analysis of compost

There is a potential concern that the applicability of these results could be limited because either: (1) TVS reduction is not a suitable measure of the quality of compost in land application, or (2) heavy metal levels in the compost could have led to atypical composting. The compost obtained after 12 days at 60% moisture and C/N ratio of 19.6 was used to carry out the germination test. The outcomes of the germination test are given in Table 5 and show 99.2% relative seed germination and 49.1% root growth; the calculated value of germination index (GI) is close to the suggested value of 60% for white radish (Diaz et al., 2003). On the other hand, poor relative seed germination (50.9%), root growth (16.4%) and GI (8.3%) values are observed with a commercial compost extract, which shows that our compost has fewer phytotoxic effects than typical compost.

The heavy metal concentrations in the compost along with their concentration limitations are tabulated in Table 6. Although some metals are at higher concentrations than for some standards, the concentrations are generally low, and so unlikely to limit the applicability of the results.

4. Conclusions

Co-composting of green waste and food waste was carried out successfully at low C/N ratios. A maximum TVS reduction of 33% was obtained in 12 days at 60% moisture and C/N ratio of 19.6. The TVS reduction obtained under all co-composting runs was fitted well by a second-order response surface plot. The TVS reduction is at its maximum under the conditions of low moisture contents and high C/N ratios, or high moisture contents and low C/N ratios. The interaction between C/N ratio and moisture content has considerable impact on TVS reduction. The compost obtained at 60% moisture and C/N ratio of 19.6 passed the germination tests, which ensure its possibility for land application. As a whole, adopting co-composting at low C/N ratios could reduce the requirement of bulking agent for adjusting C/N ratios.

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