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Bioresource Technology 99 (2008) 2210–2217

BIORESOURCE TECHNOLOGY

High-rate composting of barley dregs with sewage sludge in a pilot scale bioreactor

Li-An Lu, Mathava Kumar, Jen-Chieh Tsai, Jih-Gaw Lin *

Institute of Environmental Engineering, National Chiao Tung University, 75 Po-Ai Street, Hsinchu 300, Taiwan

Received 13 December 2006; received in revised form 14 May 2007; accepted 14 May 2007

Abstract

The feasibility of high-rate composting of barley dregs and sewage sludge was examined using a pilot scale bioreactor. A central composite design (CCD) was used to optimize the mix ratio of barley dregs/sewage sludge and moisture content. The performance of the bioreactor was monitored as a function of carbon decomposition rate (CDR) and total volatile solids (TVS) loss rate. The optimum range of mix ratio and moisture content was found to be 35–40% and 55–60%, respectively. High CO_2 evolution rate (CER) and TVS loss rate were observed after 3 days of the composting and the compost was matured/stable after 7 days. Cardinal temperature model with inflection (CTMI) was used to analyze the compost stability with respect to CER as a parameter of composting efficiency. After examining the phytotoxicity, the compost can be promoted for land application.

Keywords: Barley dregs; Central composite design; High-rate composting; Bioreactor; Sewage sludge

1. Introduction

In Taiwan, barley dregs account for about 20% of the 300,000 tons of brewery waste production per year. The disposal of barley dregs is one of the major issues due to the restrictive characteristics such as high protein, carbohydrates and cellulose contents. On the other hand, the increasing population density and industrial growth in Taiwan, generate large amount of sewage sludge at wastewater treatment plants. Handling and disposal of sewage sludge need considerable attention because of its high moisture content and in addition, it requires costly dewatering equipments (Hassouneh et al., 1999). However, barley dregs and sewage sludge constitutes valuable source of organic matter and nutrient contents. Co-composting of barley dregs and sewage sludge seems to be an attractive and viable treatment technology in which the resources in the wastes can be reused and the safe disposal is ensured.

Composting is a simple and cost-effective technology for the treatment of sewage sludge compared to the conventional methods like landfilling, incineration and ocean dumping. It is the biochemical degradation of organic materials to sanitary, nuisance free, humus like material (Kulcu and Yaldiz, 2004). Composting has been defined as a controlled microbial aerobic decomposition process with the formation of stabilized organic materials that may be used as soil conditioners and/or organic fertilizers (Golueke, 1973; Wilson and Dalmat, 1986; Buchanan and Gilessman, 1992; Garcia et al., 1992; Schlegel, 1992; Negro et al., 1999). Compost obtained under thermophilic temperature is usually stable and free of pathogens (Pena et al., 1992). The most important factors affecting the successful application of compost for agricultural purposes are its degree of stability and maturity (Said-Pullicino et al., 2007). The degree of compost stability refers to the rate or degree of organic matter decomposition expressed as a function of microbial activity and evaluated by means of respirometric measurements (Lasardi and Stentiford, 1998; Adani

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* Corresponding author. Tel.: +886 3 5722681; fax: +886 3 5725958.
E-mail address: jglin@mail.nctu.edu.tw (J.-G. Lin).

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doi:10.1016/j.biortech.2007.05.030

et al., 2003) and/or by studying the transformations in chemical characteristics of compost organic matter (Pichler and Kogel-Knabner, 2000). The sewage sludge alone produces poor quality compost due to high moisture and low organic carbon contents. As a result, the land application of compost obtained from sewage sludge has not given primary importance for land application (Spinosa et al., 1987). The application of immature and unstable compost may inhibit seed germination, reduce plant growth and damage crops by competing for oxygen or causing phytotoxicity to plants due to insufficient biodegradation of organic matter (Brewer and Sullivan, 2003; Cooperband et al., 2003; Wu et al., 2000). The addition of barley dregs with sewage sludge in composting is one of the promising ways to reduce the moisture content and increase the organic carbon of the end product.

A vast amount of composting studies was carried out with different substances and at different temperatures (Table 1). Most studies show that composting time of organic matter varies from three weeks to several months. However, reducing composting time is becoming an integral part of composting and economically beneficial (Dıaz et al., 2003; Wong et al., 2001). High-rate composting has been accepted as one of the most important process for the decomposition of organic matter because of the less space requirements and reduction in the period of operation. Some of the high-rate composting experiments carried out in the recent years are shown in Table 1. Although many composting experiments were conducted to describe the effects and/or optimize environmental factors such as temperature, aeration rates, moisture and nutrient contents (Epstein, 1997; Keener et al., 2001), the influence of the above parameters vary with the composting materials, i.e. type of waste. Moreover, so far no study has been emphasized the utilization of barley dregs for composting.

The present investigation is focused to promote the land application of compost obtained from barley dregs and sewage sludge. In order to achieve the goal, the optimum barley dregs/sewage sludge mix ratio and moisture content of high-rate composting are evaluated. A central composite design (CCD) is used to elucidate the optimum operating conditions.

2. Methods

2.1. Experimental raw materials

The barley dregs were collected from a brewery industry located at Chu-Nan, Taiwan and the sewage sludge was collected from Nei-Hu wastewater treatment plant, Taipei, Taiwan. Rice husk was used as a bulking agent to adjust the moisture content and porosity of the composting mixture. The matured compost was added along with sewage sludge as a seeding material to improve the composting efficiency. The physicochemical properties of barley dregs, sewage sludge, rice husk and matured compost are shown in Table 2.

2.2. Experimental setup

The bioreactor consists of an insulated cylindrical vessel of 100 l capacity, a spiral agitator, an online oxygen/carbon dioxide analyzer (ABB® EL1020, Germany) and a PC based data acquisition system. The schematic diagram of the experimental setup is shown in Fig. 1. Initially, barley dregs and sewage sludge were mixed together to achieve the required mix ratio as shown in Table 3. The mix ratio of sewage sludge and barley dregs was selected based on the percentage weight of sewage sludge. Exactly, 10 kg of the above mixture was added with 3 kg of rice husk and 2 kg of recycled compost. Later, the moisture content was adjusted to required level (Table 3) by the addition of tap water. The contents were mixed thoroughly in a mechanical mixer for 20 min and fed into the bioreactor manually in uniform layers. A spiral agitator was designed to operate for a period of 5 min at 5 rpm and followed by a 10 min halt using a PC based data acquisition/controlling system. The bioreactor was maintained in aerobic condition by supplying air at a rate of 1.4–2.6 l/kg VS min using an air pump and the performance of the reactor was monitored for 7 days.

2.3. Analytical techniques

At regular intervals (8 h), exactly 100 g of samples were withdrawn from the bioreactor and analyzed immediately for moisture content, TVS and pH. An online CO_2

Table 1
Comparison of different composting methods

Composting method	Substance	Reaction temperature (°C)	Composting time (days)	Reference
Aerated static pile (*D*: 2.0 m; *H*: 1.3 m)	Al-Salt wastewater sludge	73 (max)	30–45	Hassouneh et al. (1999)
Aerated static pile (*D*: 1.5 m; *H*: 0.15 m)	Gelatin-grenetine industry sludge	69 (max)	60–70	Hoyos et al. (2002)
High-rate composting (21 l)	Vinasse with cotton waste	Controlled at 55	20–35	Dıaz et al. (2003)
High-rate composting (200 l)	Food waste with office paper	74 (max)	20–30	Bari and Koening (2001)
High-rate composting (200 l)	Household waste	Controlled at 55	16–20	Smars et al. (2002)
High-rate composting (1000 l)	Food waste	Controlled at 60	20–25	Kwon and Lee (2004)

D and *H* are diameter and height of compost pile, respectively.

Table 2
Physico-chemical properties of the composting materials and compost

Constituents	Barley dregs	Sewage sludge	Rice husk	Compost (for recycling)
Moisture (%)	9.5–10.5	75.0–76.0	10.0–11.0	12.0–15.0
Ash (% dry matter)	3.7–4.0	30.0–31.0	11.5–12.0	12.0–13.0
TVS (% dry matter)	96.0–96.3	69.0–70.0	89.0–90.0	87.0–88.0
pH[a]	6.2–6.4	6.3–6.5	7.2–7.4	7.5–7.8
C (%)	47.8–49.1	36.3–36.4	41.2–41.4	41.0–42.0
H (%)	6.6–7.0	5.5–5.6	5.3–5.4	5.7–5.9
O (%)	40.5–42.8	52.0–52.3	51.8–52.3	49.5–51.0
N (%)	2.8–3.4	5.9–6.0	1.2–1.4	2.3–2.6
C/N	14.1–17.5	6.05–6.17	29.4–34.5	15.8–18.3
Electrical conductivity (μmho/cm)[a]	790–795	605–606	1036–1131	–
Ammonia Nitrogen (mg/kg of dry matter as N)	21.8	32.3	3.1	–
Phosphate (mg/g of dry matter as P)	0.047	0.68	0.26	
K (mg/g of dry matter)	0.13	0.83	2.39	
Cu (mg/kg of dry matter)	17.2	158.8	40.2	–
Cr (mg/kg of dry matter)	ND[b]	73.0	ND[b]	–
Ni (mg/kg of dry matter)	ND[b]	30.8	ND[b]	–
Zn (mg/kg of dry matter)	61.0	324.8	23.2	–
Pb (mg/kg of dry matter)	14.2	55.4	8.4	–
Cd (mg/kg of dry matter)	ND[b]	ND[b]	ND[b]	–

[a] Solid:liquid = 1:10.

[b] Not detected (MDL for Cr, Ni and Cd are 0.035, 0.024 and 0.006 mg/l, respectively).

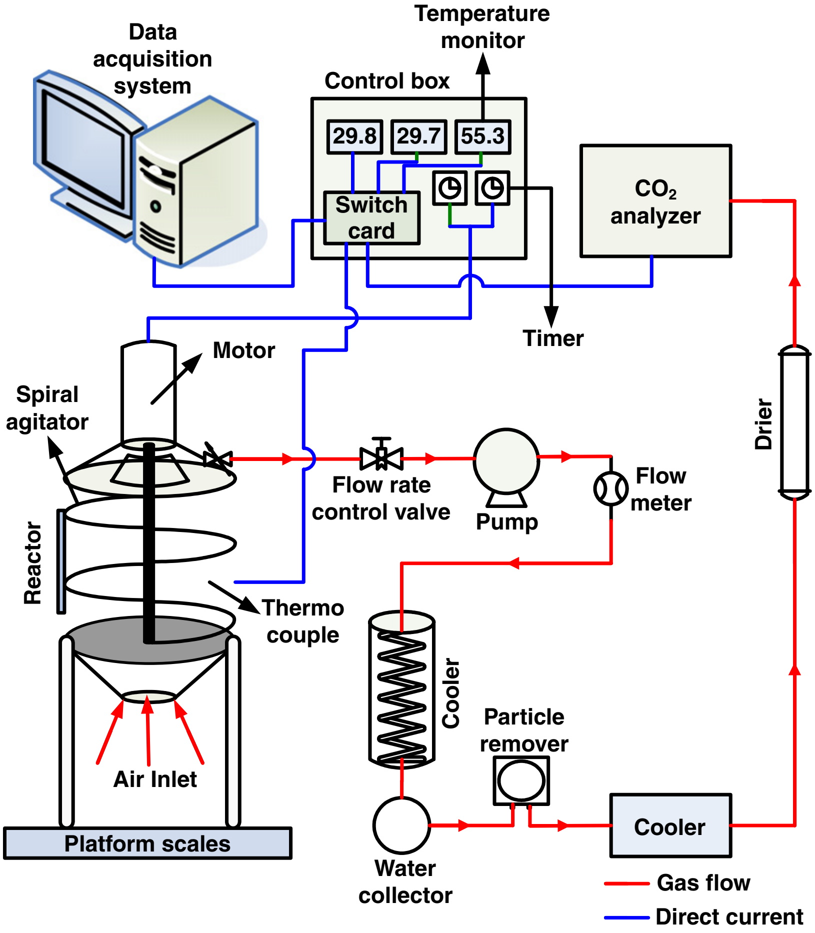

Fig. 1. Schematic diagram of the experimental setup.

Table 3
Central composite quadratic polynomial model, experimental data, actual and predicted values for five-level-two-factor response surface analysis

Run order	Aeration rate (l/kg VS min)	Independent variables		Dependent variables				Maximum temperature (°C)	Maximum CER (g CO_2/kg VS h)	Final pH	CO_2 and temperature relationship (experimental) (R^2)	CTMI model regression coefficient (R^2)
		Mix ratio (%)[a]	Moisture content (%)	CDR		TVS loss rate						
				Actual (%)	Predicted (%)	Actual (%)	Predicted (%)					
1	1.81	50 (5:5)	40	60.83	63.83	18.13	16.18	65	20.36	8.84	0.90	0.80
2	2.24	71 (7.1:2.9)	44	50.63	49.75	16.71	18.49	60	18.63	8.60	0.93	0.96
3	1.72	50 (5:5)	70	69.72	67.31	17.79	17.13	51	12.48	8.65	0.81	0.78
4	1.74	50 (5:5)	55	76.97	78.39	22.97	23.09	63	18.81	9.32	0.89	0.86
5	1.50	29 (2.9:7.1)	66	72.80	74.94	20.11	20.65	49	14.10	8.77	0.92	0.89
6	1.51	29 (2.9:7.1)	44	69.49	67.76	17.31	18.76	58	14.87	9.02	0.88	0.93
7	1.88	50 (5:5)	55	79.10	78.39	22.90	23.09	64	18.70	9.08	0.91	0.73
8	1.40	20 (2:8)	55	71.78	71.16	24.02	22.79	56	15.04	8.87	0.87	0.82
9	2.24	71 (7.1:2.9)	66	44.65	47.68	17.16	17.98	44	8.34	8.98	0.94	0.94
10	2.59	80 (8:2)	55	76.91	38.82	22.03	20.69	48	15.88	9.21	0.82	0.89
11	1.81	50 (5:5)	55	77.30	78.39	23.30	23.09	63	17.28	9.18	0.84	0.72

[a] The data presented within the parenthesis are the ratio of sewage sludge to barley dregs in kg and in all experiment the amounts of rice husk and compost (seed) addition were fixed as 3 kg and 2 kg, respectively.

analyzer (ABB EL1020, Germany) was used to measure the CO_2 evolution in the bioreactor and the corresponding CO_2 evolution rate (CER) was calculated. A thermal probe connected though an online PC based data acquisition system was used to monitor the temperature of the bioreactor continuously. The moisture content was determined at 105 °C for 24 h in a hot-air oven (ASTM, 1984) and the TVS were measured at 550 °C for 4 h in a muffle furnace (APHA, 1989). The pH was measured by using a direct reading type pH meter with glass electrode and a calomel reference electrode.

2.4. Experimental design and optimization of parameters

In order to correlate the dependent variables i.e. CDR and TVS loss rate, and independent variables i.e. moisture content and mix ratio, with the minimum possible number of experiments, a central composite design for two factors has been used. This design enables the construction of second order polynomials relating to one dependent and two independent variables. The total number of experiments (N) required for two independent variables was determined by Eq. (1) (Akhnazarova and Kafarov, 1982; Techapun et al., 2002; Dıaz et al., 2003; Gunawan et al., 2005).

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

where K represents the number of independent variables, in the present study, $K = 2$ and n_c is the center point. Predetermined ranges of independent variables i.e. mix ratio (20%, 29%, 50%, 71% and 80%) and moisture content (40%, 44%, 55%, 66% and 70%), were used for CCD and the data were analyzed using MINITAB® 14 Statistical software. Three replications of center point were selected for CCD and totally, 11 composting experiments were predicted by the software. A generalized relationship between the independent variables is proposed by Montgomery (2001) and is shown in Eq. (2).

$$X_i = \frac{X - \overline{X}}{(X_{\max} - X_{\min})/2} \tag{2}$$

where X_i is a coded value and X is the actual value, $\overline{X}$ is the average value, and $X_{\max}$ and $X_{\min}$ are maximum and minimum values of mix ratio, X_1 or moisture content, Xs_2 (independent variables). The values of two independent variables were normalized from −1.414 to 1.414 by Eq. (2) in order to obtain more accurate estimates of the regression coefficients and reduce the interrelationship between linear and quadratic terms (Montgomery, 2001).

3. Results and discussion

3.1. Monitoring the general parameters of the composting mixture

The dependent variables of the products obtained during the composting are shown in Table 3. From the results, it was observed that moisture content has more effect on dependent variables compared to mix ratio. When the moisture content was controlled within 50–60% on a wet basis, the maximum temperature and maximum CER were relatively high. The three-dimensional response surfaces for each dependent variable and their corresponding contour plots were shown in Figs. 2a to 3b. From Fig. 2a, it was observed that CDR was more influenced by mix ratio than moisture content. The total carbon content of composting feedstocks varied with different mix ratios of sewage sludge and barley dregs. CDR was gradually increased with low mix ratio and then sharply decreased when mix ratio was greater than 60%. The results inferred that composting efficiency and quality were low with high sewage sludge content. The increase in sewage sludge content along with high moisture content has decreased the maximum CER (Table 3). This may be due to the presence of low molecular fatty acids in the sewage sludge resulting from the anaerobic treatment. Margesin et al. (2006) reported the inhibition of microbial metabolism due to the presence of low molecular fatty acids during the composting of sewage sludge. In the present study, the reduction in the composting efficiency with increasing sewage sludge content in feedstocks was envisaged due to the inhibition of bacterial metabolism by low molecular fatty acids. The TVS loss rate was influenced more by moisture content compared to mix ratio (Fig. 3a). Composting was inhibited when the moisture content was less than 40%. On the other hand, the bioreactor was turned into anaerobic condition at moisture content more than 70% due to the reduction in the porosity of the composting materials. The metabolic process of the microbes is supported significantly when the moisture content was between 40% and 60% (Bertran et al., 2004). Similar trends were observed by several researchers during composting (Gajurel et al., 2003). The effect of mix ratio and moisture content on CDR and TVS loss rate are shown in Figs. 2b and 3b, respectively. The maximum CDR (>78%) was observed when the moisture content and mix ratio was 35–45% and 55–60%, respectively whereas, maximum TVS loss rate (>22%) was observed when the moisture content and mix ratio was in the range of 55–60% and 30–40%, respectively. Many researchers reported that maximum oxygen consumption rate during composting occurred at moisture content between 50% and 70% (Crawford, 1983; Bertran et al., 2004).

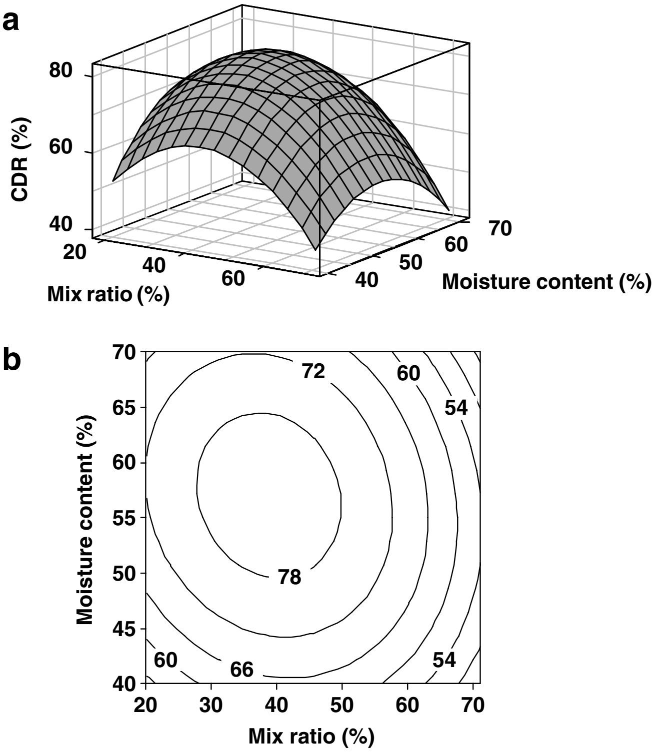

Fig. 2. Variation of CDR as a function of mix ratio and moisture content. (a) Response surface and (b) Contour plot.

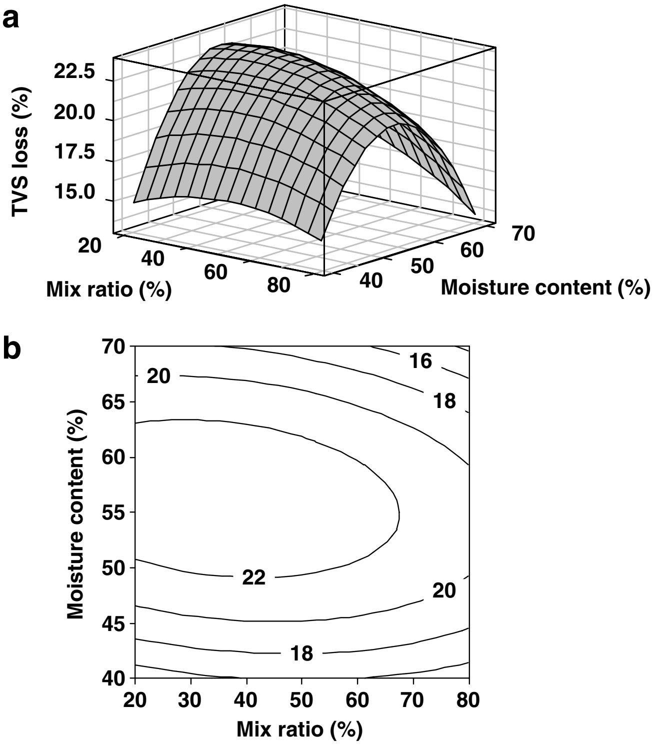

Fig. 3. Variation of TVS loss rate as a function of mix ratio and moisture content. (a) Response surface and (b) Contour plot.

3.2. Model analysis to estimate the coefficients

The results of the experimental design were analyzed by MINITAB® 14 Statistical software to derive quadratic mathematical model for CDR and TVS loss rate. The regression coefficients and the probability *P*-values for all linear, quadratic and interaction effects of the parameter on CDR are shown in Table 4. The *P*-value is used to estimate the statistical significance and its value less than 0.05 indicates that the model is considered as statistically significant (Akhnazarova and Kafarov, 1982; Techapun et al., 2002; Dıaz et al., 2003; Gunawan et al., 2005). It was

Table 4
Estimated regression coefficients and corresponding *P*-values for CDR

Component	Coefficient	Standard error	*T*	*P*
Constant	77.790	1.648	47.213	0.000
X_1	−11.947	1.303	−9.172	0.001
X_2	1.238	1.009	1.227	0.287
X_1^2	−11.728	1.485	−7.897	0.001
X_2^2	−6.395	1.236	−5.175	0.007
X_1X_2	−2.323	1.427	−1.628	0.179
Standard deviation = 2.858	$R^2 = 0.973$		$R^2_{\text{adj}} = 0.94$	

Table 5
Estimated regression coefficients and corresponding *P*-values for TVS loss rate

Component	Coefficient	Standard error	*T*	*P*
Constant	23.0567	1.0378	22.216	0.000
X_1	−0.7955	0.6355	−1.252	0.266
X_2	0.3461	0.6355	0.545	0.609
X_1^2	−0.6833	0.7564	−0.903	0.408
X_2^2	−3.2158	0.7564	−4.251	0.008
X_1X_2	−0.5875	0.8988	−0.654	0.542
Standard deviation = 1.798	$R^2 = 0.80$		$R^2_{\text{adj}} = 0.61$	

Table 6
Comparison of the simulated data of TVS loss rate and CDR with actual experimental data

Item	TVS loss rate (%)	CDR (%)
Quadratic models[a]	23.32	81.27
Experimental set 1[b]	22.01	74.20
Experimental set 2[b]	27.40	73.56

[a] The value simulated by the quadratic models obtained from experimental design.

[b] The experimental value obtained while mix ratio and moisture content controlled at 37% and 57%, respectively.

observed that coefficients for all effects were highly significant except the effects of moisture content (X_2) and the interaction effect between mix ratio/moisture content, i.e. X_1X_2 (Table 4). In addition, a high R^2 value (0.94) indicates that second-order polynomial model is adequate to represent the actual relationship between the responses.

From Table 5, only quadratic effects of moisture content were significant (Techapun et al., 2002; Dıaz et al., 2003; Gunawan et al., 2005). It was observed that R^2 of TVS loss rate was 0.80 and adjusted R^2 was 0.61 (Table 5). The difference of these two values was significantly high due to the other insignificant terms in the model. Generally, insignificant variables are screened out to derive high R^2 value. However, they were included in this study under the restriction of Hierarchy principle (Montgomery, 2001). The quadratic model is shown in Eqs. (3) and (4).

$$Y_1 = 77.79 - 11.95X_1 + 1.24X_2 - 11.73X_1^2 - 6.40X_2^2 - 2.32X_1X_2 \tag{3}$$

$$Y_2 = 23.06 - 0.80X_1 + 0.35X_2 - 0.68X_1^2 - 3.22X_2^2 - 0.59X_1X_2 \tag{4}$$

where Y_1 and Y_2 are CDR and TVS loss rate, and X_1 and X_2 are the coded variables of mix ratio and moisture content, respectively. From Table 3, it can be seen that a high correlation was observed between the experimentally observed and predicted values. However, to confirm the applicability of the quadratic model (Eqs. (3) and (4)); two batch-composting sets with external replicates from the optimum operating conditions were conducted. The mix ratio and moisture content were controlled at 37% and 57%, respectively. The experimental results were compared with the simulated results of quadratic model (Table 6). From the results, it was observed that the quadratic model shown in Eqs. (3) and (4) is in good agreement with the experimental results.

3.3. Evaluation of compost stability

Compost stability is strongly related to the rate of decomposition of the organic matter (OM), as expressed by the biological activity. Compost stability is estimated based on both volatile solids decomposition rate as well as by carbon dioxide (CO_2) evolution. The OM degradation was in relation to the OM loss, which was directly related to the microbial respiration (Paredes et al., 2002). Although volatile solids decomposition rate and CO_2 production rate can be used to quantify the compost stability, the results of TVS loss rate inferred that compost stability could be accurately indicated by CER (Nakasaki et al., 1993; Wong and Fang, 2000; Kulcu and Yaldiz, 2004; Kwon and Lee, 2004). This finding was in good agreement with Zmora-Nahum et al. (2005), where they reported that compost stability is assessed widely by respiration as measured by either O_2 uptake or CO_2 evolution. From Table 3, it was observed that CER was directly proportional to temperature. During composting, the organic carbon is converted into CO_2 and it is mainly influenced by temperature (Said-Pullicino et al., 2007). Therefore, CER can be correlated to the transfer rate of substrate during composting and can be used as an evaluating index to assess the variation of substrate.

Although modeling the physical aspects of moisture removal is relatively straightforward, the biological aspects are considerably more complex. Cardinal temperature model with inflection (CTMI), as shown in Eq. (5) (Rosso et al., 1993) was selected to analyze CER during composting of barley dregs and sewage sludge. The R^2 values of eleven runs in this study were ranging from 0.53 to 0.92. The results reflect that CTMI was not completely fitted with the variation of CER ($R^2 \leqslant 0.92$), however; the experimental results were in good correlation with the CTMI model (Fig. 4).

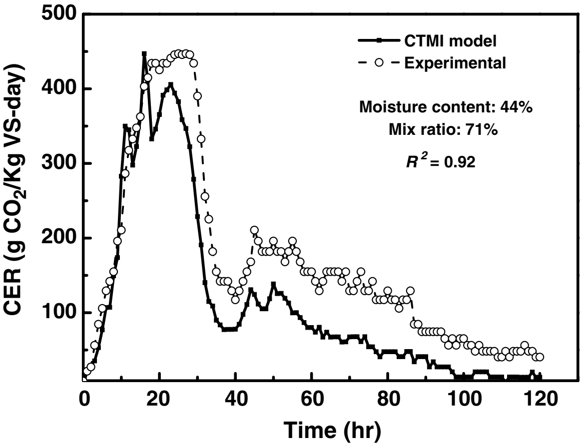

Fig. 4. Comparison of CER obtained from CTMI model with experimental data.

$$\mathrm{RCO_2} = \left[\frac{R_{\mathrm{CO_2opt}}(T - T_{\max})(T - T_{\min})^2}{(T_{\mathrm{opt}} - T_{\min})[(T_{\mathrm{opt}} - T_{\min})(T - T_{\mathrm{opt}}) - (T_{\mathrm{opt}} - T_{\max})(T_{\mathrm{opt}} + T_{\min} - 2T)]}\right] \tag{5}$$

where $\mathrm{RCO_2}$ is the CER (g CO_2/kg VS day), $R_{\mathrm{CO_{2opt}}}$ is the CER at maximum temperature (g CO_2/kg VS day), T_{opt} is the maximum temperature of composting (°C), and $T_{\min}$ and $T_{\max}$ are the minimum (15 °C) and maximum (70 °C) temperature for biodegradation, respectively.

The variation of CER during composting is shown in Fig. 5. The high CER indicate elevated microbial respiration of the readily available carbon in the composting mixture. However, CER was reduced to 3.25 g CO_2/kg VS h at 120 h and further reached to 1.49 g CO_2/kg VS h at 160 h (Fig. 5). This value was below one-tenth of maximum evolution rate (18.8 g CO_2/kg VS h). The decrease in the CER with composting time is because of the reduction in metabolic activity due to the decrease of readily available carbon. Roger (1979) reported that the composting product found to be stabilized when CER decreased to one-tenth of maximum value. The variation of temperature during active phase (Fig. 6) follows a similar trend to that of the CER measurements, with maximum temperature being recorded during first 80 h and a steady decrease thereafter. The temperature of the bioreactor was greater than 55 °C for more than 1.5 days and the temperature exceeding 60–65 °C would kill almost all the microorganisms/pathogens in the waste materials (Said-Pullicino et al., 2007; Zhang and He, 2006). The establishment of these thermophilic conditions is due to the self-heating of organic matter as a result of microbial respiration. However, the temperature was clearly declined to ambient temperature to about 30 °C after 5–7 days of composting and later remained stable which is shown as a sign of composting stabilization (Wilson and Dalmat, 1986).

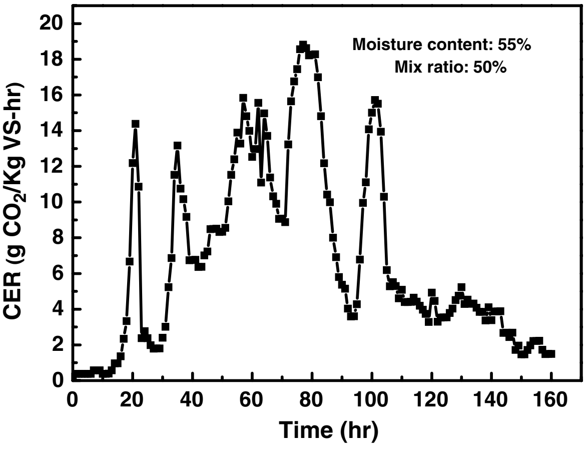

Fig. 5. Variation of CER during composting process.

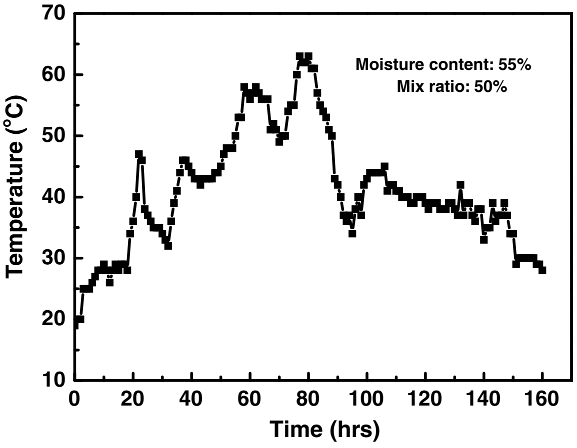

Fig. 6. Variation of temperature during composting process.

4. Conclusions

The results obtained indicate that composting can be an environmental-friendly alternative to solve the disposal problems of barley dregs and sewage sludge. High-rate composing process reduced the duration of composting drastically. The variation of temperature and CER during composting was highly correlative and the second-order polynomial model formulated in the study can be used to predict the CDR and TVS loss rate during composting. After conducting germination tests, the compost obtained from barley dregs and sewage sludge can be promoted to land application.

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