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Evaluation of thermochemical pretreatment and continuous thermophilic condition in rice straw composting process enhancement

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HIGHLIGHTS

- ▶ Biodegradability of rice straw will be improved after alkali pretreatment.
- ▶ CBITPCP as a novel method is very significant on enhancing of rice straw composting.
- ▶ Maturated compost products were obtained after composting for 9 days in the CBITPCP.

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ABSTRACT

The effects of thermochemical pretreatment and continuous thermophilic conditions on the composting of a mixture of rice straw residue and cattle manure were investigated using a laboratory-scale composting reactor. Results indicate that the composting period of rice straw can be shortened to less than 10 days by applying alkali pre-treatment and continuous thermophilic composting conditions. The parameters obtained on day 9 of this study are similar to the criteria level published by the Canadian Council of Ministers of the Environment. The moisture content, organic matter reduction, pH level, electrical conductivity, total organic carbon reduction, soluble chemical oxygen demand reduction, total Kjeldahl nitrogen, carbon-to-nitrogen ratio, and germination index were 62.07%, 16.99%, 7.30%, 1058 μS/cm, 17.00%, 83.43%, 2.06%, 16.75%, and 90.33%, respectively. The results of this study suggest that the application of chemical–biological integrated processes under thermophilic conditions is a novel method for the rapid degradation and maturation of rice straw residue.

1. Introduction

The conversion of rice straw into value-added compost may improve crop productivity, reduce environmental pollution, and reduce local pollution caused by open burning (Roca-Pérez et al., 2009; Zayed and Abdel-Motaal, 2005). However, the chemical composition of rice straw is mainly lignocellulose, which is not readily biodegradable (Drapcho et al., 2008).

Pretreatment is performed to break the matrix, reduce the degree of cellulose crystallinity, and increase the amorphous cellulose fraction, which is one of the most suitable forms for enzymatic attack (Sanchez and Cardona, 2008). Alkaline and acid pretreatments involve the application of chemical solutions, such as NaOH, KOH, or H_2SO_4 to remove lignin and some of the hemicelluloses (Hosseini et al., 2012; Zhang et al., 2011). Several studies have indicated that alkali pretreatment is one of the most effective methods used to make the hemicellulose materials soluble (Hosseini et al., 2012; Zhang et al., 2011).

Temperature is one of the most frequently used indexes to determine the progress of the composting process (Li et al., 2008). A high amount of organic matter (OM) decomposes under thermophilic conditions. A high rate of biooxidation of organic materials begins at 40 °C (Hamoda et al., 1998). The increase in temperature in the composting pile results in an increase in the rate at which chemical bonds in substrate compounds are broken. Microbial activities can also be enhanced by increasing the temperature to 28–55 °C (Tang et al., 2004). However, (Xiao et al., 2009) indicated that the duration of the municipal solid waste (MSW) composting process decreases from 28 to 14 days by using a continuous thermophilic composting method at 50 °C. Other studies have also indicated that maximum thermophilic composting activity occurs at temperatures in the range of 50–60 °C (Tang et al., 2007). The composting period of the MSW organic fraction is also decreased to 40 days under thermophilic aerobic composting conditions (Elango et al., 2009). These results are consistent with those in another study, in which the effect of temperature on composting of cattle manure and rice straw for 21 days was investigated (Li et al., 2008). In particular, the composting process was performed under mesophilic (30–45 °C) and thermophilic (55–66 °C)

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conditions, and results indicated that the thermophilic condition is more efficient in enhancing the composting process based on OM reduction than the mesophilic condition (Tang et al., 2007). The moisture content (MC), carbon-to-nitrogen ratio (C:N), degree of aeration, pH level, and physical structure of the raw materials are some of the important factors that affect the composting process (Li et al., 2008). The results of related studies are discussed in Table 1.

This study used a novel method, chemical–biological integrated thermophilic composting process (CBITPCP), for composting rice straw, in which rice straw was pretreated under an alkali thermochemical condition and subjected to a thermophilic phase during the entire composting process.

2. Methods

2.1. Collection of materials

The resource materials used for composting mainly consisted of rice straw and cattle manure. Rice straw samples were collected from a local wet paddy rice field at Sungai Dua in Penang, Malaysia. Fresh cattle manure was taken from a local cattle farm near the engineering campus of USM at Nibong Tebal in Penang, Malaysia. The straw was initially cut to lengths of 5–10 cm, thoroughly washed with tap water, and then air-dried for 24 h. Grinding, which reduces the particle size, is usually the initial pretreatment for any biomass followed by storage in a cold room (temperature $\leqslant 4$ °C). Fresh cattle manure was air-dried for 24 h, and then stored in a cold room (temperature $\leqslant 4$ °C).

2.2. Thermochemical pretreatment

Our previous study indicated that the optimum condition for enhancing the solubility of rice straw is obtained at a temperature of 200 °C, a detention time of 180 min, and NaOH concentration of 0.6 g NaOH/g rice straw (Hosseini et al., 2012). Therefore, 250 g of chopped rice straw (2 mm) was pretreated under this optimum condition. After the pretreated samples were neutralized with diluted H_2SO_4, the rice straw was dried at 70 °C for 24 h before CBITPCP use.

2.3. Experimental setup

The rice straw and cattle manure mixer was placed in two Pyrex glass cylinder reactors (5000 mL capacity) and a perforated plate was added to distribute air supplied by air compressors at the bottom of the reactors. CBITPCP samples were placed in a water bath to control the temperature under thermophilic condition; normal composting process (NCP) samples were subjected to ambient and mesophilic conditions (Fig. 1).

CBITPCP experiments were performed using rice straw (250 g) that was pretreated with alkali. Dried and shredded rice straw (250 g) was used in NCP experiments without pretreatment. Rice straw, dried manure, and distilled water were initially mixed to a specific ratio to produce an initial MC of 70% and a C:N of approximately 25. The resulting mixture was then packed into CBITPCP and NCP reactors. The pH of the mixture in both reactors was adjusted to approximately 7.5. The temperature of the water bath was maintained at 40 °C on day 1, and then raised to 50 °C during the remaining 44 days of thermophilic composting (Xiao et al., 2009). Air was supplied through perforated polyvinylchloride tubes at a rate of 2 L/min kg volatile solid using aquarium aerators (Li et al., 2008). The compost reactors were manually turned every 24 h. Samples (5 g wet weight) were collected daily from each reactor immediately after manual turning. Temperature, pH, electrical conductivity (EC), MC, OM, total organic carbon (TOC), total Kjeldahl nitrogen (TKN), C:N, and GI were evaluated to determine the compost stability and the compost maturity. Finally, CBITPCP results were compared with those of NCP.

2.4. Analytical parameters

Reactor temperatures were maintained using a water bath and monitored with a digital thermometer before daily sampling. The pH of aqueous extracts (w:v = 1:10) was measured using a pH digital meter (pH 510, EUTECH, USA) and an EC meter (VSI, Model 30 M, 100FT, USA) according to US Environmental Protection Agency (USEPA) 9045D and Standard Method 2510-B.

MC of the raw materials was determined by drying the samples at 105 °C for 24 h (ASTM-D2974). Ash was determined in a muffle

Table 1
Evaluation of influences operational parameters on rice straw composting.

Raw materials	Influence factor	Result	References
Rice straw contains with farmyard manure	Rock phosphate and *Aspergillus niger*, *Trichoderma viride*	The C:N ratio in final compost was decreased from 46:1 to 20:1 after 105 days	Zayed and Abdel-Motaal (2005)
A mixture of air-dried rice straw, fresh buffalo's manure	10% of rock phosphate and MC 50–60%	The EC and OM were declined. TKN increased. GI for optimum condition was 83.38% after 90 days. The minimum pH at the end of composting process	Rashad et al. (2010)
Rice straw and sewage sludge	Shredded and non-shredded rice straw	The C:N value for final product was 10 from an initial value of around 20 after 90 days. Maximum GI of 106% was obtained after 90 days of composting	Roca-Pérez et al. (2009)
Rice straw with dairy manure	Size reduction of raw materials, MC and aeration rate	C:N, VS and total solid values in final compost 52.3, 75.7 and 59.2% was reduced respectively	Li et al. (2008)
Cattle manure with rice straw	The influences of temperature	Thermophilic condition is more significant on enhancement of composting	Tang et al. (2007)
Rice straw and fresh farmyard manure	Quantity and particle size	C:N ratio of final product reached to 13:1 from 30:1 in initial C:N after 75 days	Hatem et al. (2009)
Rice straw	Lignocellulolytic fungi	After 3 weeks C:N value reach to 19.5 from an initial value of 29.3	Kausar et al. (2010)
Rice straw with poultry manure	Poultry manure and oilseed rape cake	After 90 days C:N ratio and GI reach to 13.3–8.9 and 71.1–81.6%	Abdelhamid et al. (2004)
Swine manure with rice straw	As nutrient balances, aeration rate, temperature and MC	Optimum condition is obtained at a low initial C:N ratio after 63 days.	Zhu (2007)
Pig manure with sawdust	Different C:N	In optimum condition was obtained at low C:N ratio after 49 days	Huang et al. (2004)
Rice straw	Sewage sludge	The optimum results was obtained at lower C:N value (17)	Iranzo et al. (2004)
Food waste	In-vessel method	The C:N ratio in final product reached to 17 from an initial of 24 after 30 days	Kim et al. (2008)

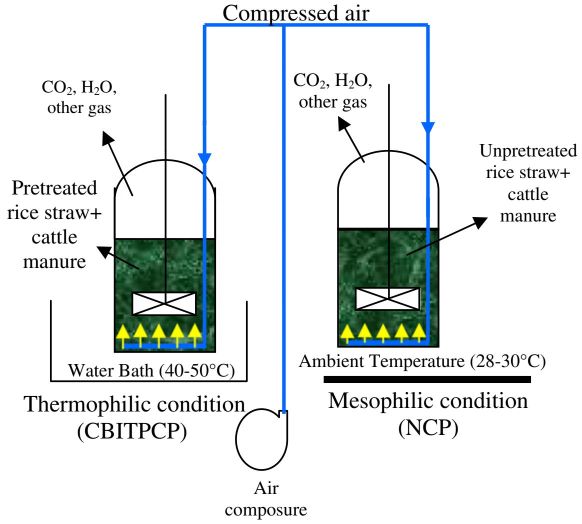

Fig. 1. Comparison schematic of two bio-composting reactor setups used in this study.

furnace at 550 °C for 24 h; OM (%) was calculated as the difference between ash and its dry weight (ASTM-D2974, 2007). An adequate volume of water was added at each turn to maintain approximately 60–70% MC. In this study, the TKN and TOC contents were determined according to American Public Health Association 4500-N_{org}-B and modified Walkley–Black method (Eaton et al., 2005).

Germination index (GI) and root elongation were used to evaluate the negative effects of compost on plant growth (CCQC, 2001). Aqueous compost extracts were used to evaluate the inhibitory effect on GI and root elongation. Fresh samples (10 g with a solid:DDW ratio of 1:10 w:v, dry weight basis) were taken from each run and agitated for 1 h. Ten cress seeds (*Lepidium sativum*) were placed on Whatman No. 1 filter paper in a Petri dish with a diameter of 10 cm, where approximately 2 ml of each extract was added. Distilled water (2 ml) was used as the control sample. Triplicate samples were analyzed for each run. The Petri dishes were incubated on a laboratory bench for 48 h at ambient temperatures.

The number of germinated seeds was counted, and the lengths of roots were measured. The GI was calculated according to the formula as described previously (Huang et al., 2004).

2.5. Compost maturity evaluation

The purpose of this study was to determine optimal operating conditions for thermochemical pretreatment. The effect of pretreatment on the stability, maturity, and enhancement of the rice straw composting process under mesophilic and thermophilic conditions was also investigated. Improvement of stability and maturity using CBITPCP was evaluated by assessing the indexes of reaction temperature, pH level, EC, MC, OM, TOC, soluble chemical oxygen demand (SCOD), TKN, C:N, GI, microbial pollution, and optimum composting period. The results were compared with those of NCP.

C:N, often used as an index of compost maturity (Brito et al., 2012; Rashad et al., 2010) is calculated from TOC and TKN values. In California, compost is considered mature when the C:N is <25 and in China when the C:N is 15–25 (CCQC, 2001; Xiao et al., 2009).

Compost stability refers to the rate of OM decomposition (Xiao et al., 2009). Readily biodegradable OM is degraded by microorganisms during composting to CO_2 and water. The final product is stable; i.e., biodegradation is slow (Petric et al., 2012).

During the composting process, a direct relationship exists between microbial activity and temperature exhibit: high temperatures are enhanced by the composting process. The temperature should be maintained at a maximum of 65 °C (Tang et al., 2007). The final decrease in temperature is one of the most reliable factors to evaluate compost maturity because variation in composting temperature is directly affected by microbial activity (Diaz et al., 2004).

Variation in pH is another parameter used to monitor the composting process (Huang et al., 2011). In the first stage of composting, organic acids (such as formic acid, acetic acid, and pyruvic acid) are formed, thereby decreasing the pH to approximately 5.0. These acids are subsequently consumed by microorganisms, and the pH increases until it stabilizes at approximately 7.0 (or as high as 8.5) in mature compost (Rashad et al., 2010).

The EC value decreases as the composting process continues because soluble compounds are consumed as nutrients by microorganisms, and some compounds, such as ammonia and mineral salts, are volatilized or precipitated. An EC of <1500 $\mu S\ ml^{-1}$ is acceptable for mature composte to be used as soil amendment (Rashad et al., 2010). GI of mature compost should be >90% of the control GI (CCQC, 2001).

The surface of rice straw is soft and irregular due to small vascular bundles in the sub-epidermal sclerenchyma and the accumulation of silica (Pan et al., 2010). The physical structure is monitored to evaluate the lignocellulose waste maturation (Li et al., 2008). In this study, the effects of the thermochemical pretreatment and composting process on the surface morphology of the rice straw fiber were evaluated under a scanning electron microscope (SEM) by Quanta FEG450 model.

2.6. Statistical analysis

IBM SPSS statistics 19 for Windows was used to analyze the composting process data. One-way ANOVA was used to test the significant differences between the treatments.

3. Results and discussion

3.1. Physicochemical properties of raw materials

Physicochemical parameters were selected based on the effectiveness of composting process parameters (Table 2). The selected physicochemical properties of rice straw residues and cattle manure indicated that rice straw has low MC (9.19%), high carbon (43.17%), and low TKN (0.653%). In contrast, cattle manure exhibited opposite properties. Hence, a mixture of rice straw and cattle manure provide suitable MC and balanced nutrients for the microorganisms involved in the composting process (Li et al., 2008).

3.2. Monitoring the compost process

The selected stability and maturity indexes, including temperature, pH, EC, MC, OM, TOC, TKN, SCOD, C:N, and GI were monitored

Table 2
Selected physicochemical properties of raw composting materials.

No	Parameters	Rice straw	Cattle manure
1	MC (%)	9.19	74.65
2	OM (%)	88.4	77.99
3	TOC (%)	43.17	35.3
4	TKN (%)	0.653	2.35
5	C:N	66.11	19.61
6	pH	7.15	7.79
7	EC ($\mu S\ m^{-1}$)	2381	1378

Table 3
Comparison stability and maturity indexes between normal composting process (NCP) and chemical biological integrated thermophilic composting process (CBITPCP) with composting time.

Days	MC (%)		OM (%)		PH		EC (μS/cm)		TOC (%)		SCOD (%)		TKN (%)		C:N		Temperature (°C)	
	NCP	CBITPCP	NCP	CBITPCP	NCP	CBITPCP	NCP	CBITPCP	NCP	CBITPCP	NCP	CBITPCP	NCP	CBITPCP	NCP	CBITPCP	NCP	CBITPCP
1th	75.12	75.65	87.95	86.91	7.63	7.20	557	1856	42.54	41.58	3.62	8.57	1.70	1.60	25.60	25.99	29	40
2th	72.36	79.66	87.75	78.94	7.64	7.00	529	1436	42.56	37.77	3.60	5.29	1.72	1.68	24.37	22.48	28	54.5
3th	70.52	77.29	87.72	78.16	7.62	6.95	510	1682	42.5	37.39	3.61	5.11	1.71	1.71	24.72	21.87	28	51
4th	69.41	75.27	87.65	76.43	7.58	6.63	492	1735	42.36	36.57	3.59	4.18	1.70	1.74	23.58	21.02	29	55
5th	76.32	72.76	87.54	75.21	7.52	6.30	528	1657	42.25	35.98	3.58	3.67	1.68	1.76	23.25	20.44	30	57
6th	75.14	68.92	86.12	74.74	7.57	6.41	569	1422	42.15	35.76	3.52	2.98	1.71	1.83	22.52	19.54	31	55
7th	71.02	64.74	85.36	73.51	7.54	6.90	595	1248	42.08	35.17	3.47	2.32	1.69	1.98	22.31	17.76	32	54
8th	78.73	62.19	85.10	72.83	7.42	7.18	629	1129	41.95	34.85	3.44	1.76	1.71	1.97	21.69	17.69	32	53
9th	73.11	62.07	84.72	72.14	7.38	7.30	672	1058	42.10	34.51	3.45	1.42	1.715	2.06	21.17	16.75	32	52
11th	68.56	56.16	84.30	71.54	7.3	8.05	681	976	41.80	34.23	3.32	1.29	1.728	2.14	20.44	16.00	31	52
13th	63.85	58.37	84.10	71.53	7.15	8.12	645	968	41.58	34.22	3.26	1.11	1.73	2.16	20.13	15.84	32	51
15th	76.09	56.35	83.66	71.73	7.10	8.15	735	945	41.12	34.32	3.07	1.07	1.75	2.17	19.59	15.82	33	51
17th	75.76	54.28	83.25	70.72	6.90	8.30	761	897	40.68	33.83	2.89	1.02	1.765	2.21	19.28	15.31	32	51
19th	72.45	72.36	82.02	70.27	6.81	8.28	784	890	40.14	33.62	2.73	1.10	1.78	2.23	18.49	15.08	33	51
21th	71.63	70.72	81.18	69.51	6.72	8.22	798	887	39.43	33.26	2.59	1.02	1.82	2.19	18.35	15.19	34	51
25th	62.68	61.58	80.24	70.16	6.62	8.20	766	885	38.15	33.57	2.26	0.92	1.837	2.20	18.18	15.26	31	50
35th	75.56	78.39	79.15	68.85	6.51	8.20	656	880	37.88	32.94	2.10	0.87	1.84	2.25	17.97	14.64	29	50
45th	73.31	59.79	79.78	68.71	7.18	8.10	486	883	37.64	32.87	1.86	0.76	1.83	2.30	17.73	14.29	28	50

during the composting period of 45 days (Table 3). The results from NCP and CBITPCP experiments were compared with one-way ANOVA (Table 4). Table 4 shows that all of the indexes from the two treatments significantly varied except SCOD ($P_{pH} \geqslant 0.229$). This result indicates that the pretreatment and thermophilic conditions significantly affect the stability and maturity of rice straw composting for this time period.

3.2.1. Temperature

The temperature used for NCP was ambient under mesophilic conditions. However, CBITPCP was maintained at 40 °C on day 1, and then increased to 50 °C during the remaining 44 days. Fig. 2a shows the changes in composting temperature for NCP and CBITPCP. Temperatures ranged from 28 to 34 °C and 40 to 57 °C for NCP and CBITPCP, respectively ($P_{NCP\cdot CBITPCP} = 0.000$). NCP and CBITPCP reached their maximum temperatures after days 21 and 5, respectively. The change in OM, TOC, TKN, pH, EC, and C:N corresponded to the change in temperature. Continuous mixing and aeration prevented the temperature from exceeding the maximum value.

3.2.2. pH

pH variation for NCP and CBITPCP followed the same pattern; in particular, pH decreased to 6.51 and 6.30 on days 35 and 5, respectively. The conversion of OM to acidic compounds started sooner in CBITPCP than in NCP because a higher degradability was observed in the pretreated rice straw under the continuous thermophilic condition than that in non-pretreated rice straw under the mesophilic condition. However, the pH level in the composting process cannot exceed a specific range, e.g., 4–10. pH increased to 7.18 and 8.10 at the end of the composting period (Fig. 2b). Statistical analyses showed that no significant difference was found between NCP and CBITPCP ($P_{NCP\cdot CBITPCP} = 0.132$) because of the limited range of obtained data for NCP and CBITPCP. Previous studies found that pH dropped below 6 during the initial phase of composting because of organic acids produced from the breakdown of sugars and fats by bacteria (Sundberg and Jönsson, 2005). Acceptable pH ranges are tolerable for microorganisms, e.g., bacteria, fungi, and actinomycetes, which generally survive in a pH range of 6–7.5, 5.5–8.0, and 5.0–9.0, respectively (Cheung, 2008).

3.2.3. EC

The salinity and suitability of compost for crop growth were evaluated using the EC index. NCP and CBITPCP showed a different pattern of changes in EC (Fig. 2c). The EC of NCP increased from the beginning of the composting period. The maximum EC was obtained on day 21 for NCP. After the peak value was reached, EC steadily decreased until the end of the composting period. The initial increase was likely due to the biotransformation of complex material structures to simple compounds, such as ammonium and phosphate. However, the decrease in EC values at the end of the composting period may be caused by the biodegradation of water-soluble substances, such as organic acids, during the composting process (Tang et al., 2004). However, EC of CBITPCP decreased from day 1 to day 3 of the composting period because the dissolved and readily biodegradable substances were consumed in the biooxidation process. The CBITPCP temperature also increased during this period, indicating the increase in biological activity. The maximum EC was observed on day 4 and EC increased at the end of the composting period. The EC reduction in CBITPCP (52.42%) was significantly higher than that in NCP (12.45%; $P_{NCP\cdot CBITPCP} = 0.000$), which can be attributed to the higher compound transformation rate of the complex rice straw structure into simple compounds in CBITPCP than that in NCP. The comparison of EC values of the final products between NCP and CBITPCP indicates

Table 4
One-way ANOVA of the stability and maturity indexes of normal composting process (NCP) and chemical biological integrated thermophilic composting process (CBITPCP).

Parameter		Sum of squares	df	Mean square	*F*	Sig.
OM (%)	Between groups	1063.847	1	1063.847	73.685	0.000
	Within Groups	490.886	34	14.438		
	Total	1554.733	35			
EC (μS/cm)	Between groups	2800602.250	1	2800602.250	42.614	0.000
	Within groups	2234502.056	34	65720.649		
	Total	5035104.306	35			
pH	Between groups	0.780	1	0.780	2.378	0.132
	Within groups	11.156	34	0.328		
	Total	11.937	35			
TOC (%)	Between groups	314.885	1	314.885	83.705	0.000
	Within groups	127.902	34	3.762		
	Total	442.787	35			
SCOD (%)	Between groups	3.674	1	3.674	1.503	0.229
	Within Groups	83.116	34	2.445		
	Total	86.790	35			
TKN (%)	Between Groups	0.631	1	0.631	22.516	0.000
	Within groups	0.952	34	0.028		
	Total	1.583	35			
CN	Between groups	94.738	1	94.738	10.851	0.002
	Within groups	296.844	34	8.731		
	Total	391.582	35			
Temperature (°C)	Between groups	3885.444	1	3885.444	480.285	0.000
	Within groups	275.056	34	8.090		
	Total	4160.500	35			

that CBITPCP products have less phytotoxic/phytoinhibitory effects on plant growth if applied on soil.

3.2.4. OM

OM decreased from 87.95% to 79.78% and from 86.91% to 68.71% after 45 days in NCP and CBITPCP, respectively. Therefore, the consumption of OM in NCP and CBITPCP was 9.29% and 20.94%, respectively. The conversion rate of OM in CBITPCP was 225% higher than that in NCP because of the enhancement of the composting process under continuous thermophilic condition and high digestibility of pretreated rice straw (Abdelhamid et al., 2004; Rashad et al., 2010; Zayed and Abdel-Motaal, 2005). These results (Fig. 2d) suggested that compost microorganisms feed on OM for their anabolic and catabolic processes. Heat, CO_2, and water vapor are produced during this process. OM content in CBITPCP was less than that in NCP, indicating that the rate of decomposition in CBITPCP is higher than that in NCP ($P_{NCP\cdot CBITPCP} = 0.000$).

3.2.5. MC

Li et al. showed that a higher initial MC (65%) and a more stable end compost of rice straw was obtained using a longer retention time of high temperature with dairy manure (Li et al., 2008). In this study, the initial MC of the composting materials was adjusted to 70–75% (Table 3) to reach a high temperature and produce more mineralized final compost.

3.2.6. SCOD

The SCOD concentration decreased from 3.62% to 1.86% and from 8.57% to 0.76% for NCP and CBITPCP, respectively. The SCOD reduction for NCP and CBITPCP was 91.13% and 48.62%. In other words, the conversion rate of SCOD reduction for CBITPCP was 187% higher than that in NCP. However, the difference of the results was not significant ($P_{NCP\cdot CBITPCP} = 0.229$): the mean value for the two samples is almost same.

3.2.7. TKN

TKN increases with process time because of the net loss of dry mass and organic C as CO_2 during composting. Moreover, total N can be increased through bacterial nitrogen fixation at the end of the composting process (Abdelhamid et al., 2004; Brito et al., 2012). The TKN values increased from 1.70% to 1.83% and from 1.60% to 2.30% for NCP and CBITPCP, respectively (Fig. 2f). TKN value of CBITPCP is 428% higher than that of NCP. Statistical analyses showed that a significant difference in OM was found between NCP and CBITPCP ($P_{NCP\cdot CBITPCP} = 0.000$).

3.2.8. C:N

C:N correlates well with the degree to which composting is completed (Kim et al., 2008). In NCP, C:N was reduced to 20.57 from an initial value of 25.02 after 45 days of rice straw biodegradation (Fig. 2g). In the CBITPCP process, C:N was greatly reduced compared with that in the NCP process and matured compost; in particular, the C:N value was decreased to 16.57 and 14.29 from an initial value of 25.99 after 9 days and at the end of the composting period, respectively. *F*-test analyses revealed a significant difference in C:N between NCP and CBITPCP ($P_{NCP\cdot CBITPCP} = 0.002$), in which C:N reduction in CBITPCP is 146% higher than that in NCP. Results from others studies indicated that the optimum C:N ratio after 84 days (Rashad et al., 2010), 28 days (Li et al., 2008) and 20 days (Xiao et al., 2009) was 16, 13.3 and 20, respectively. These results were obtained with a longer period of composting and are higher than the results of this study. Compost maturation depends on various conditions, such as the characteristics of the raw materials, operational composting parameters, and ambient conditions. Therefore, C:N in the solid phase cannot be used as an absolute index of compost maturation. However, a value of $\leqslant 17$ can be considered satisfactory (Kim et al., 2008).

3.2.9. GI

GI for very mature, mature, and immature samples are $\geqslant 90\%$, 80–90%, and $\leqslant 80\%$, respectively, compared with that of the control sample (CCQC, 2001; Ko et al., 2008). Researchers usually consider

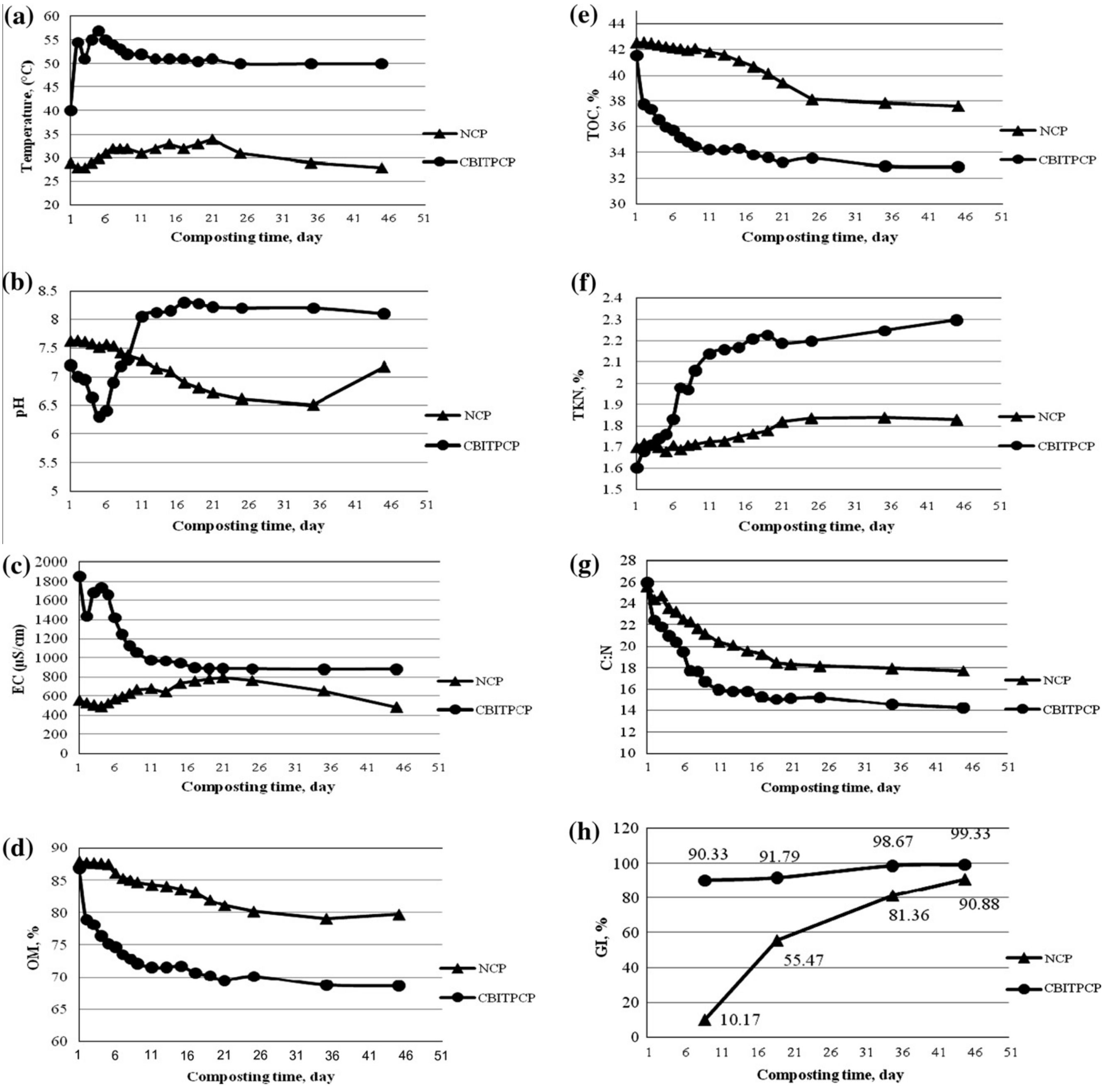

Fig. 2. Comparison of variation of temperature (a), pH (b), EC (c), OM (d), TOC (e), TKN (f), C:N (g), and GI (h) during composting process between normal composting process (NCP) and chemical biological integrated thermophilic composting process (CBITPCP).

that a sample is a mature compost if the GI value is >90% (Xiao et al., 2009). In NCP, GI was 90.88% after 45 days, whereas GI was 90.33% and 99.33% after 9 and 45 days in CBITPCP, respectively (Fig. 2h). This result confirmed that the sample was free of phytotoxins, which indicates that the compost will have a positive effect on plant growth. In other studies, optimum GI was obtained after a longer period of compost, i.e. after 84 days (Rashad et al., 2010), 63 days (Zhu, 2007) and 14 days (Xiao et al., 2009).

3.2.10. SEM

The surface porosity increased after composting because of the biotransformation of hemicellulose and other soluble compounds of rice straw (Pan et al., 2010). However, the erosion of the rice straw surface significantly increased under alkali pretreatment and continuous thermophilic conditions because of the high decomposition rate of biodegradable compounds in NCP. The results of study shows that the rice straw surface in CBITPCP was decomposed at a higher rate than that in NCP in terms of higher erosion and mineralization rates. Therefore, the erosion and the changes in the rice straw microstructure under NCP and CBITPCP treatments as well as the removal of lignin and hemicellulose compounds were significantly higher under the CBITPCP condition.

3.2.11. Decreasing the composting period

Some disadvantages of composting include long processing time and the large space required, which limit the development of the composting industry (Raut et al., 2008). The conventional composting process requires 2–6 months to allow the biotransformation of

Table 5
Characteristics of compost content for normal composting process (NCP) and chemical biological integrated thermophilic composting process (CBITPCP) treatments at 9th day of experiments.

Parameters	Treatments		Standard[*]
	NCP	CBITPCP	
MC (%)	73.11	62.07	40–80
OM reduction (%)	3.67	16.99	–
pH	7.38	7.30	7–8.5
EC (μS/cm)	672	1058	1500
TOC reduction (%)	1.03	17.00	–
SCOD reduction (%)	4.50	83.43	–
TKN (%)	1.715	2.06	–
C:N	24.55	16.75	15–20
GI (%)	10.17	90.33	90

[*] Canadian Council of Ministers of the Environment (CCME, 2005).

raw materials into mature compost. Therefore, decreasing the composting process time of particular interest for further research (Lin, 2008).

Several studies attempted to enhance the composting of rice straw to decrease the composting process time and improve the stability and maturity of the final product (see Table 1). Grinding the raw materials to less than 5 mm, applying specific microorganisms, adding nutrient elements to raw materials, and changing the operational conditions (e.g., the MC, C:N, aeration rate, and temperature) have been used in such studies (Table 1). However, the CBITPCP method used in this study significantly enhances the composting reaction rate and shortens the composting cycle by using the continuous thermophilic composting of alkali thermochemical pretreated rice straw and cattle manure at a proper mixture ratio. The composting period of the rice straw and cattle manure mixture can be shortened to less than 10 days by using the CBITPCP method. Based on the results obtained in CBITPCP on day 9, the parameters were approximately equal to those published by the Canadian Council of Ministers of the Environment or other researchers. For example, after composting has started, the MC, OM reduction, pH level, EC, TOC reduction, SCOD reduction, TKN, C:N, and GI were 62.07%, 16.99%, 7.30, 1058 μS/cm, 17.00%, 83.43%, 2.06%, 16.75, and 90.33%, respectively (Table 5). Results from others studies indicated that the maturated compost obtained after 105 days (Zayed and Abdel-Motaal, 2005), 90 days (Roca-Pérez et al., 2009), 84 days (Rashad et al., 2010), 28 days (Li et al., 2008) and 20 days (Xiao et al., 2009). As a general conclusion, CBITPCP reduced rice straw composting period from 2–6 months to 9 days. This indicates that the required area for the Windrow composting method or required volume for an in-vessel reactor can be decreased by at least 85%.

4. Conclusions

The results of the present investigation can be summarized as follows. The alkali pretreatment and the continuous thermophilic condition are very important in reducing the composting process time. The CBITPCP method can significantly enhance the composting reaction rate and shorten the composting cycle. The parameters used in this study are within their recommended range and the compost produced using CBITPCP complied with the established standard. This study recommends CBITPCP as a novel method for the rapid degradation and maturation of rice straw residue.

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