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Kinetics for degradation of bisphenol A during aerobic composting of sewage sludge and sawdust

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ABSTRACT

To investigate the kinetics of the degradation of bisphenol A (BPA) by aerobic composting of sewage sludge (SS) and the effects of the major controlling factors, six pilot-scale (5 L) and 10 bench-scale (0.5 L) trials were conducted using sawdust as the amendment. For BPA with initial concentrations of 0.349–0.551 mg kg^{-1} in pilot-scale trials, half the BPA was removed within the first 2.5–7.5 d of the 14-d composting process. Fitting the pilot-scale BPA reduction data to first-order kinetic models indicated that degradation rate constants and half-lives for BPA ranged from 0.095 to 0.175 d^{-1} and from 4.0 to 7.3 d, respectively. Kinetic parameters were obtained from bench-scale trials under various controlling factors such as initial concentration of BPA, aeration, moisture content and temperature. The results showed that thermophilic aerobic biodegradation was the main mechanism for BPA removal during the aerobic stabilization phase of SS composting. The optimum conditions for BPA degradation were 0.3–30 mg kg^{-1} initial concentration, 0.050–0.100 L min^{-1} kg^{-1} aeration rate, 60%–70% moisture content and 60°C–70°C temperature. Our findings could be used to further the enhancement of BPA biodegradation in SS or other solid wastes.

Keywords: Bisphenol A; Sewage sludge; Composting; Degradation; Kinetics

1. Introduction

Bisphenol A (BPA), as a typical environmental endocrine-disrupting chemical, has become one of the most ubiquitous contaminants in the environment [1,2]. Large amounts of BPA have been applied as plasticizers to produce polycarbonate and epoxy resin in the production of various plastics and paper coatings. During the production process and product usage, a proportion of BPA dissolves and may enter the environment. Recent research has shown that BPA could influence multiple endocrine-related pathways and generate adverse effects even below the lowest observed effect level, which was established by the EPA in 1988 and adapted by the FDA [3]. Therefore, the fate and removal of BPA in the environment has drawn considerable attention from both environmental scientists and the public. Municipal wastewater treatment plants (WWTPs) are considered the main pollution sources for BPA in the environment [4,5].

To date, the occurrence and fate of BPA in WWTPs has been well documented by several studies [6,7]. Because of its high hydrophobicity, BPA can be easily transferred from wastewater to sewage sludge (SS) [8,9]. Therefore, BPA of influent wastewater is gathered in SS, where the BPA concentrations are thousands of times greater than those in effluent wastewater [10,11]. As a result, SS may be considered a

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substituted pollution source of BPA for wastewater, and thus the potential exposure risk of BPA in SS should be paid more attention than that in effluent wastewater. A number of recent studies have reported the ecological risk of BPA in various environmental media such as the aquatic environment [12], organisms [13,14] and the soil [15]. However, few studies have focused on the potential exposure risk in agricultural soil amended by SS or SS compost, even though BPA contents of more than 100 mg kg^{-1} have been observed in SS from China [16].

Two main disposal routes have been applied for dewatered SS from WWTPs: land application after composting or digestion, and land filling after drying or incineration. Compared with land filling, land application of SS has obvious advantages including recycling of nutrients and improvement of soil properties and has been adopted widely across the world [17]. Given that composting is an extensively adopted treatment before land application of SS, it is necessary to assess the removal efficiency and potential ecological risk of BPA during the composting process. Some studies have shown that composting is one efficient method for removing organic microcontaminants in SS or other solid wastes. Oleszczuk [17] found a significant decrease of 14 polycyclic aromatic hydrocarbons (PAHs) of SS during the composting process over 70 d. Wu et al. [18] showed that three tetracyclines in swine manure were biodegraded over 70% after composting for 53 d, and the degradation process of three tetracyclines successfully fitted an adjusted first-order kinetic model. Removal of BPA has been found through four pathways in terrestrial and aquatic environments: microbiological degradation, photodegradation, phytodegradation and algal degradation [19]. Of these, biodegradation by microorganisms is the most probable pathway during composting of SS. Since biodegradation of BPA has only been found among aerobic organisms to date [19], the main influencing factors include initial concentration, temperature, moisture content and sufficient aeration. To our knowledge, no studies have reported the kinetics and its factors for degradation of BPA during the SS composting process, which is key information for improving removal efficiency and reducing potential ecological risk of BPA for land application of SS.

Therefore, there were two aims of the current study: (1) investigation of the occurrence and fate of BPA in SS during the composting process and determining the reaction kinetics parameters for degradation of BPA during composting process and (2) exploration of the optimum ranges of main factors such as initial concentration of BPA, aeration, moisture and temperature to remove BPA by aerobic composting of SS. The findings of this study could be used to enhance the removal technology of BPA based on composting of SS.

2. Materials and methods

2.1. Raw materials and chemical reagent

SS was obtained from a WWTP located in the urban region of Guilin, south China, where the thickened sludge was dewatered via a belt-filter press. Sawdust collected from a local wood-processing facility was used as the amendment to improve the C/N ratio, free air space and moisture content of SS [20]. The SS and sawdust was mixed manually to form a homogeneous mixture.

Ultrapure water was prepared by an ultrapure water purifier (Milli-Q Plus, Millipore, MA). The BPA (99%) and BPA-d16 (98%) were obtained from Dr. Ehrenstorfer GmbH (Augsburg, Germany), each of which was dissolved in an appropriate amount of methanol for preparation of the stock solution (1 g L^{-1}). Methanol (MeOH), dichloromethane (DCM), acetone and hexane were pesticide-residue grade and were purchased from Merck (Darmstadt, Germany). The derivatization reagent, Bis-(trimethylsilyl)-trifluoroacetamide (BSTFA) with 1% of trimethylchlorosilane (TMCS) was obtained from Sigma-Aldrich (St. Louis, USA). An Oasis HLB cartridge (500 mg, 6 mL) was obtained from Waters (Milford, MA) for solid phase extraction (SPE). Two types of clean-up cartridges, silica gel cartridge (500 mg, 6 mL) and acid aluminum oxide cartridge (500 mg, 6 mL), were purchased from Agela (Beijing, China).

2.2. Experimental design of composting

Composting experiments were conducted at two bioreactor scales (0.5 and 5.0 L) constructed from polymethylmethacrylate (PMMA). The 0.5-L PMMA bioreactor (80 mm internal diameter, 200 mm depth) was coated with a water-bath jacket to control the temperature of the compost matrix. The wall of the 5-L PMMA bioreactor (150 mm diameter, 400 mm depth) was covered with 10-mm-thick polyurethane as the protective coating to reduce heat loss. Air was aerated into the matrix from the bottom of the bioreactor by an air pump, and inlet airflow was measured using an airflow meter with a range of 0–0.25 L min^{-1}.

Composting tests were conducted under six different conditions in 5.0-L bioreactors for pilot-scale experiments (Table 1) and 10 different conditions in 0.5-L bioreactors for bench-scale experiments (Table 2). In the pilot-scale experiments, three different constant aeration rates (0.025, 0.050 and 0.075 L min^{-1} kg^{-1}) and three initial moisture contents (approximately 55%, 65% and 75%) were established in Trials A1–A3 and A4–A6, respectively. No additional BPA was spiked into the SS or sawdust in Trials A1–A6. The duration of the pilot-scale experiment was 14 d. In the bench-scale experiments, 10 trials labeled B1–B10 were conducted to simulate effects of three levels of four parameters on biodegradation of BPA during the first 5 d of composting (aerobic stabilization phase). This 5-d period was chosen on the basis of the results from pilot-scale trials. The four parameters and corresponding levels were as follows: BPA concentration of 15, 30 and 60 mg kg^{-1}, aeration rates of 0, 0.050 and 0.100 L min^{-1} kg^{-1}, initial moistures of 50%, 60% and 70%, and temperatures of 30°C, 45°C and 60°C, respectively. Before mixing with sawdust in Trials B1–B10, each 20-g SS (dw, dry weight) was continuously stirred and slowly spiked with 300, 600 or 1,200 μL of a stock solution containing BPA to make SS with initial BPA concentration of 15, 30 or 60 mg kg^{-1}. These concentrations were chosen on basis of the results (0.42–152 mg kg^{-1}) of a national BPA investigation in SS in China [16]. The stirring of SS and subsequent mixture ensured that the concentration of BPA in SS was the same in all parts of the reactor. Each trial was performed in triplicate.

2.3. Analysis methods

The moisture content, organic matter (OM) levels were analyzed according to the standard methods [21]. The total

Table 1
Aeration rate and initial moisture content for SS and sawdust composting processes in the pilot-scale trials

Trials	Aeration rate ($L\ min^{-1}\ kg^{-1}$)	Initial moisture content (wb[a], %)	SS sawdust (wb, m/m)	C/N ratio	Wet weight (kg)
A1	0.025	65.7	4:1	26.5	1.6
A2	0.050	66.7	4:1	25.8	1.6
A3	0.075	67.1	4:1	26.2	1.6
A4	0.053	55.4	3:1	33.5	1.5
A5	0.050	65.2	3:1	34.1	1.6
A6	0.050	74.9	3:1	33.5	1.6

[a] wb indicates wet basis.

Table 2
Different conditions of composting processes in the bench-scale trials

Trials	Addition concentration ($mg\ kg^{-1}$)	Aeration rate ($L\ min^{-1}\ kg^{-1}$)	Initial moisture (wb[a], %)	Temperature control
B1	15	0.050	61.2	Temperature for trials of B1–B7 was set as followed: 40°C (1 d), then 55°C (3 d), and then 50°C (1 d)
B2	30	0.050	60.8	
B3	60	0.050	60.8	
B4	30	0	60.5	
B5	30	0.100	60.4	
B6	30	0.050	50.7	
B7	30	0.050	69.8	
B8	30	0.050	60.3	Temperatures were held on 30°C, 45°C and 60°C for B8, B9 and B10, respectively
B9	30	0.050	60.1	
B10	30	0.050	60.1	

[a] wb indicates wet basis.

carbon and total nitrogen levels were determined by an element analyzer (PerkinElmer EA2400II, Waltham, MA). The thermal probes connected with a real-time computerized control system were used to continuously monitor the temperature of the matrix and the ambient air. Temperature data were collected from the computer, which logged data every 5 min.

Lyophilized SS and composting samples were ground to pass through a 100-mesh (0.15 mm) nylon sieve, and then were homogenized to 0.5 g (dw). The homogenized sample was spiked with 50 ng BPA-d_{16} and left for 6 h in a fume hood to complete the volatilization of solvent hexane. A two-step microwave-assisted extraction, developed by our group and described in detail in previous research [7], was used to extract samples with MeOH of 9 and 6 mL successively. The supernatant was diluted and acidified to pH of 3. Then, SPE was applied to clean up and concentrate the acidified supernatant with 8 mL of acetone:DCM solution (3:7, v/v). Sequential purification procedures with a silica gel cartridge and acidic Al_2O_3 cartridge were subsequently applied to clean up the impurity of the dilution with 10 mL methanol:acetone solution (1:1, v/v). Finally, the cleaned extract was further concentrated to 0.5 mL under a moderate stream of pure N_2. Next, 50 μL of BSTFA with 1% TMCS was added to the dried sample and then incubated at 70°C for 50 min to compete the derivatization of BPA. The derivatized sample was evaporated to dryness by N_2 again and then re-dissolved in 200 μL of hexane for gas chromatography–mass spectrometry (GC–MS) analysis.

A Clarus 600 mass selective detector linked to a Clarus 670 GC (PerkinElmer, Germany) was used to analyze the BPA. The instrument was equipped with a HP-5MS column (30 m × 0.25 mm inner diameter, 0.25 μm film thickness, PerkinElmer, Germany). The temperature of the injector and ion source were maintained at 280°C and 250°C, respectively. Each sample (1 μL) was injected in splitless mode. The oven temperature was set as the following procedure in sequence: maintained at 100°C for 1 min, raised to 250°C at the rate of 20°C min^{-1}, raised to 270°C at the rate of 5°C min^{-1}, then raised to 300°C at a rate of 20°C min^{-1}, and finally maintained at 300°C for 2 min. The MS acquisition was performed in the positive electron impact mode (70 eV) under full ion scan mode (50–600, m/z) for qualitative analysis and then the selected ion mode was used to quantify BPA (m/z value, 73, 207 and 257).

2.4. Quality assurance and quality control

The linear regression of standard curve showed a good fit ($R^2 = 0.989$). The limit of quantification was estimated at about 1 μg kg^{-1} based on the signal–noise ratio of 10. The spiking experiment was set at a BPA concentration of 50 μg kg^{-1} for solid samples ($n = 3$), and a high recovery (92% ± 9%) was obtained.

2.5. Kinetic model

It is assumed that the dissipation of organic compounds during the composting process follows the simple first-order kinetic model [22,23], and this assumption was used in this study. The kinetic equation (Eq. (1)) was expressed as follows:

$$C_t = C_0\, e^{-kt} \tag{1}$$

where C_t represents the concentration (mg kg^{-1}) of the target chemical at time t, and k is the rate constant (d^{-1}). The half-life was calculated using Eq. (2):

$$t_{1/2} = (\ln 2)/k \tag{2}$$

3. Results and discussion

3.1. Physiochemical characteristics of substrate

The physiochemical properties of the substrate are shown in Table 3. The BPA concentrations of SS added into the mixtures were approximately 0.35 and 0.55 mg kg^{-1} (dry basis) in September and November 2014, respectively. The sawdust contained no detectable BPA.

3.2. Pilot-scale composting

3.2.1. Temperature, OM and pH of the matrix

Matrix temperature in all pilot-scale trials except A6 (Fig. 1(a)) all generally went through mesophilic, thermophilic and cooling phases as the ambient temperature increased slightly during the bench-scale composting. The t_{50} values (accumulative time when the temperature of central matrix was over 50°C) were 6, 5 and 6 d for Trials A2, A3 and A5, respectively, which satisfies the requirements of the sanitary standard for composting of night soil in China. However, the compost Trials A1, A4 and A6 did not meet these requirements with t_{50} of 1, 3 and 0 d, respectively. The OM in all trials had a general declining trend (Fig. 1(b)), which was comparable to the results from other research [17,18]. The highest change of 17.2% for OM was observed in Trial A5 throughout the composting process. In contrast, OM in Trial A6 only achieved the reduction of 5.6%, which may be attributed to the insufficient biodegradation of OM under the high initial moisture content and low central temperature during composting. The pH value observed in each trial was in the range of 6.5–8.7 (Fig. 1(c)), which is suitable for the activity of aerobic microorganisms.

3.2.2. Degradation of BPA

The degradation of the BPA was also investigated in the pilot-scale trials (Fig. 2). The initial concentrations of BPA were in the range of 0.540–0.551 mg kg^{-1} for Trials A1–A3, and 0.349–0.355 mg kg^{-1} for Trials A4–A6. After the 14-d composting process, a significant reduction of BPA occurred in each pilot-scale trial. The removal efficiency of BPA ranged from 83.3% to 90.2% in Trials A1–A3, and from 69.6% to 87.3% in Trials A4–A6. The high removal efficiency indicates that composting is an effective treatment for elimination of BPA in SS. Even though BPA could not be removed completely by the fast composting technique in this study, it was degraded

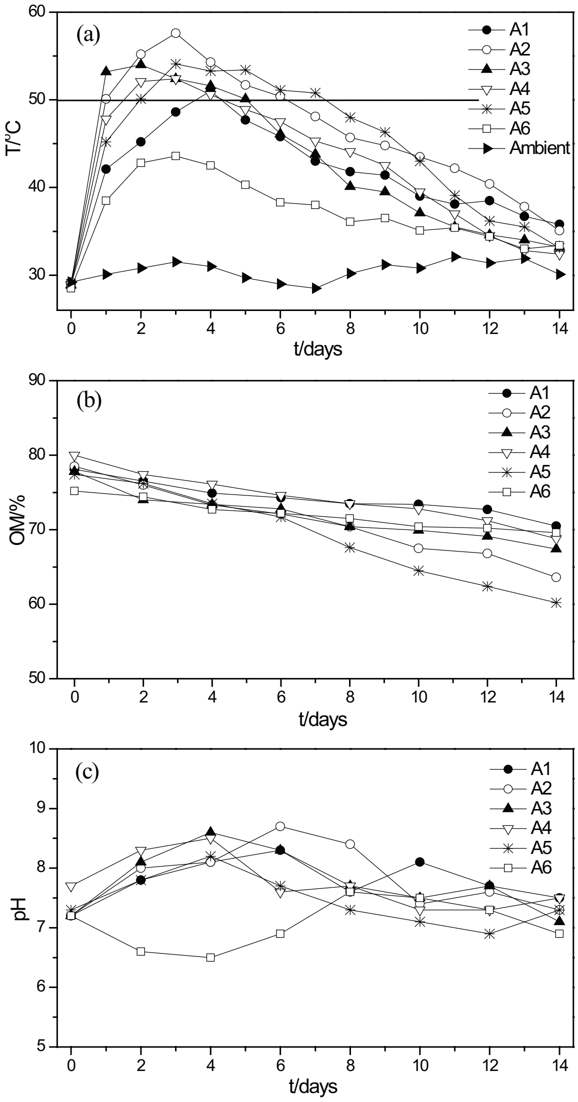

Fig. 1. Variations of (a) temperature, (b) OM content and (c) pH during the SS and sawdust composting processes in the pilot-scale trials.

Table 3
Physiochemical properties of raw materials for composting of SS and sawdust

	Moisture content (%)	Organic carbon (db[a], %)	Organic nitrogen (db, %)	C/N	pH	Organic matter (db, %)
SS	83.2 ± 0.2	44.4 ± 0.7	3.4 ± 0.2	13.0	7.5 ± 0.2	58.3 ± 2.1
Sawdust	8.4 ± 0.1	56.3 ± 0.2	0.6 ± 0.1	93.8	–	83.0 ± 1.6

[a] db indicates dry basis.

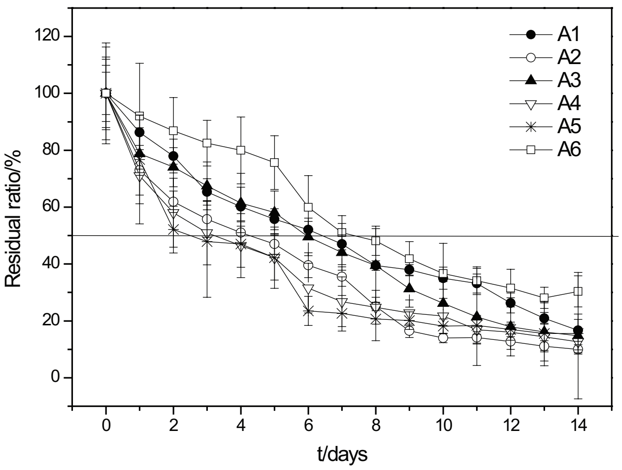

Fig. 2. Residual ratios of BPA during the SS and sawdust composting processes in the pilot-scale trials.

about approximately half of the initial concentration within the first 2.5–7.5 d. Moreover, there was little reduction of BPA when its concentration was reduced to near 0.100 mg kg^{-1}. During composting, BPA in SS was possibly degraded by bacteria and fungi with major intermediates such as nitro-BPA, dinitro-BPA, 4-isopropenylphenol, BPA-dimethyl ether, BPA-monomethyl, 4-hydroxybenzoate, hydroquinone, 4-hydroxyacetophenone, 4-hydroxycumyl alcohol and 4-isopropenylphenol [19]. Compared with the parent compound, some biodegradation products showed an increased toxicity [24] but others showed remarkable detoxification [25]. Therefore, the toxicity effect of BPA metabolisms should also be examined for the safe utilization of compost from SS.

The removal efficiency of BPA in Trial A2 was higher than those in Trials A1 and A3, which indicated that moderate aeration rate (0.050 L min^{-1} kg^{-1}) had a more positive effect on the biodegradation of BPA. Considering the higher value of t_{50} in Trial A2, the higher temperature may be the direct cause of this positive effect, under the additional influence of the aeration intensity. The high initial moisture content (75%) could produce a moderate negative effect on the biodegradation of BPA of SS by composting, since the lowest removal efficiency of BPA (70%) was observed in Trial A6. The order of total removal efficiencies of BPA in Trials A1–A6 was as follows: A2 < A4 < A3 < A5 < A1 < A6. This is different to the results based on OM reduction (Figs. 1(b) and 2). Therefore, given its status as a micropollutant, BPA had different degradation characteristics to the total organic compounds in the matrix of SS and sawdust.

3.2.3. *Kinetics for degradation of BPA*

Fitted curves were obtained by fitting experimental results for the degradation of BPA during the SS composting process with the first-order kinetic model (Fig. 3). The correlation coefficients were all >0.93 (Table 4), suggesting that the first-order kinetic model can be successfully used to describe the dissipation process of BPA during composting. The half-life of BPA in the matrix (Table 4) ranged from 4.0 to 7.3 d, which was comparable with the result of 7 d in the non-sterile aerobic soil according to Ying and Kookana [15]. The lowest and highest BPA half-life values occurred in Trials A5 and A6, respectively, which corresponded to the different t_{50} values of the matrix in these trials (6 d for A5 and 0 d for A6). Therefore, the temperature may be considered an important factor for the biodegradation of BPA during composting. Zhao et al. [26] also found that the higher temperature significantly enhanced the degradation behavior of BPA in aerobic-activated sludge under the range of 10°C–30°C.

3.3. *Bench-scale aerobic stabilization*

3.3.1. *Effects of initial concentration*

The degradation of BPA under different initial concentrations is shown in Fig. 4(a) for the initial 5 d of SS and sawdust co-composting. Removal efficiency of BPA decreased from 56.6% to 32.1% with the increase of initial concentration from 15 to 60 mg kg^{-1}. This indicates that the high initial concentration of BPA could inhibit the biodegradation of BPA in a matrix of SS and sawdust. Deng et al. [27] also reported a similar phenomenon when the initial concentration of BPA was at 10–20 mg L^{-1}. This may be attributed to the toxic effect of BPA on the organisms under high initial concentrations [28].

The degradation behavior of BPA during composting fitted well to the simple first-order kinetic model in the bench-scale trials (Table 5). Based on the fitting results, half-lives of BPA increased rapidly from 4.1 to 9.1 d in Trials B1–B3, which corresponded to the inhibition of BPA under high concentration. Therefore, according to $t_{1/2}$ results for both pilot-scale and bench-scale trials, the appropriate concentration range is 0.3–30 mg kg^{-1} for biodegradation of BPA in SS during the aerobic stabilization phase of composting.

3.3.2. *Effects of aeration and moisture content*

Fig. 4(b) shows the changes of BPA concentrations under different aeration rates and initial moisture contents during the aerobic stabilization phase of composting. Removal efficiency varied as follows: B5 (56.2%) > B2 (45.9%) > B4 (19.3%). This shows that the degradation of BPA was significantly influenced by the aeration rate of composting. In particular, the amount of BPA removal reduced in Trial B4 when the aeration level was low. Therefore, the biodegradation of BPA occurred mainly in an aerobic environment, which was in accordance with the conclusions of previous research. For example, Kang and Kondo [29] found that BPA was rapidly biodegraded (>90%) under aerobic conditions, but there was barely any reduction in BPA (<10%) under anaerobic conditions lasting 10 d. Ronen and Abeliovich [30] showed that the BPA in anaerobic slurry was not biodegraded even after incubation for 3 months. Moreover, BPA could persist for an extended period under some anaerobic environments such as anaerobic marine sediment [31]. Therefore, the matrix should be provided sufficient aeration (0.050–0.100 L min^{-1} kg^{-1}) to maintain aerobic status of the matrix during composting.

With the increase of moisture content of matrix from 50.7% to 69.8% (Table 2), the removal efficiency of BPA was also enhanced from 37.3% to 56.3% (Fig. 4(b)) and $t_{1/2}$ was reduced from 7.7 to 4.9 d (Table 5). A sufficient moisture content plays a vital part in the water activity, which is a key factor in the biodegradation of BPA. However, an excessive

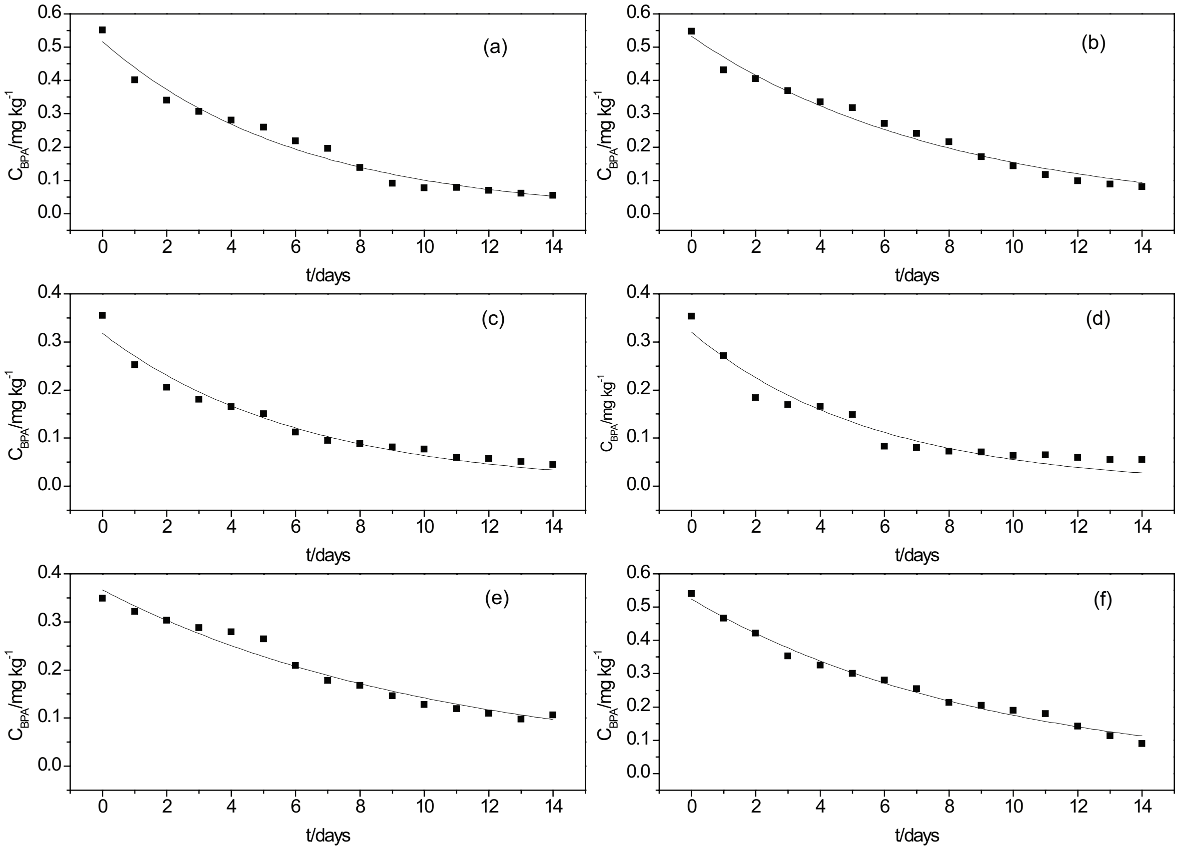

Fig. 3. Degradation kinetics of BPA during the composting process of SS and sawdust in the pilot-scale trials (black discrete square represents experimental data; black curve represents the fitted curve based on experimental data). Panels (a), (b), (c), (d), (e) and (f) represent data for Trials A1, A2, A3, A4, A5 and A6, respectively.

Table 4
Fitting results for degradation kinetics of BPA in the pilot-scale trials using simple first-order kinetic equations

Trials	C_0 (mg kg^{-1})	Rate constant k (d^{-1})	R^2	$t_{1/2}$ (d)
A1	0.524	0.110	0.988	6.3
A2	0.517	0.164	0.973	4.2
A3	0.533	0.124	0.979	5.6
A4	0.318	0.161	0.966	4.3
A5	0.320	0.175	0.936	4.0
A6	0.367	0.095	0.966	7.3

moisture content could also increase the mass transfer resistance of O_2 and correspondingly decrease the biodegradation rate of BPA (Table 5). Therefore, 60%–70% would be the optimal range for the degradation of BPA during aerobic composting of SS and sawdust.

3.3.3. *Effect of temperature*

The removal efficiencies of BPA observed in Trials B8–B10 were 28.8%, 40.8% and 91.7%, respectively (Fig. 4(c)). Compared with the other two trials, the highest degradation of BPA was achieved in Trial B10, which may be because an appropriate microorganism community was present under the temperature range of 60°C–70°C. According to the temperature curves of Trials B8–B10 (Fig. 5), thermophilic bacteria were the major microorganisms in both Trial B9 and Trial B10, whereas mesophilic bacteria were dominant in Trial B8. Therefore, thermophilic bacteria have a better treatment potential than mesophilic bacteria for the biodegradation of BPA in SS. Among enzyme systems catalyzing biodegradation of BPA, laccase is considered the major functional enzyme for its higher thermostability than other enzymes such as cytochrome P450 at the thermophilic range of 50°C–60°C [32,33]. It is therefore necessary to allow a sufficient lag period during the thermophilic phase to improve the removal efficiency of BPA by composting of SS.

4. Conclusions

Half of the BPA in SS was degraded within the first 2.5–7.5 d during aerobic composting with initial BPA concentrations of 0.350–0.550 mg kg^{-1}. Removal of BPA from SS during pilot-scale composting fitted well with first-order kinetics, with k and $t_{1/2}$ for BPA ranging from 0.095 to 0.175 d^{-1} and from 4.0 to 7.3 d, respectively.

Kinetic analysis revealed that aerobic biodegradation with thermophilic microorganisms was the main mechanism for the degradation of BPA in SS during aerobic stabilization phase of composting process. The optimum conditions for

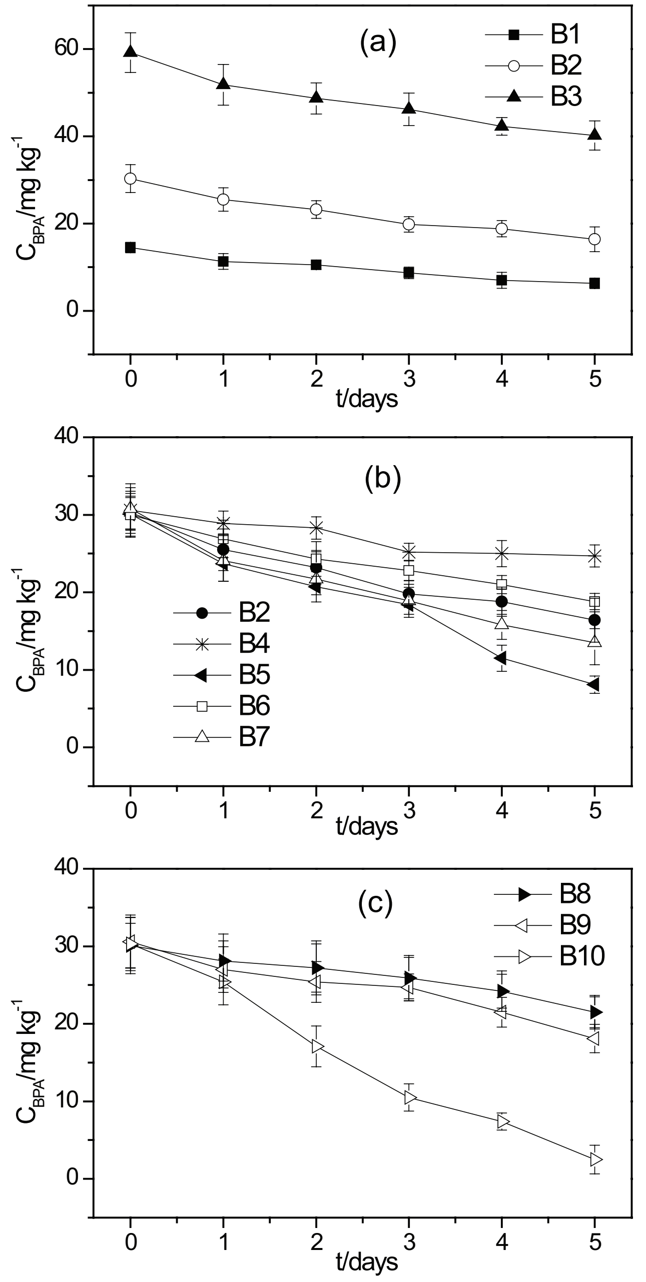

Fig. 4. Changes of BPA concentration during the SS and sawdust composting processes in bench-scale trials: (a) for trials under different initial concentrations of BPA; (b) trials under indifferent aeration rates and moisture contents; and (c) trials under different temperatures.

removal of BPA by aerobic stabilization of SS were as follows: initial BPA concentration of 0.3–30 mg kg^{-1}, aeration rate of 0.050–0.100 L min^{-1} kg^{-1}, moisture content of 60%–70% and temperature of 60°C–70°C.

These conclusions are important for the enhancement of the removal technology of BPA in SS through aerobic composting, which is used in controlling the environmental risk of BPA in the land utilization of compost derived from SS. On the other hand, these are also could be used to further enhancement of BPA biodegradation in other solid wastes.

Table 5
Fitting results for degradation kinetics of BPA in the bench-scale trials using a simple first-order kinetic model

Trials	C_0 (mg kg^{-1})	Rate constant k (d^{-1})	R^2	$t_{1/2}$ (d)
B1	14.4	0.167	0.972	4.1
B2	29.4	0.120	0.970	5.8
B3	57.5	0.076	0.986	9.1
B4	30.2	0.047	0.818	14.7
B5	31.2	0.237	0.936	2.9
B6	29.7	0.090	0.992	7.7
B7	29.8	0.157	0.980	4.4
B8	30.5	0.064	0.945	10.8
B9	31.0	0.095	0.904	7.3
B10	33.2	0.381	0.949	1.8

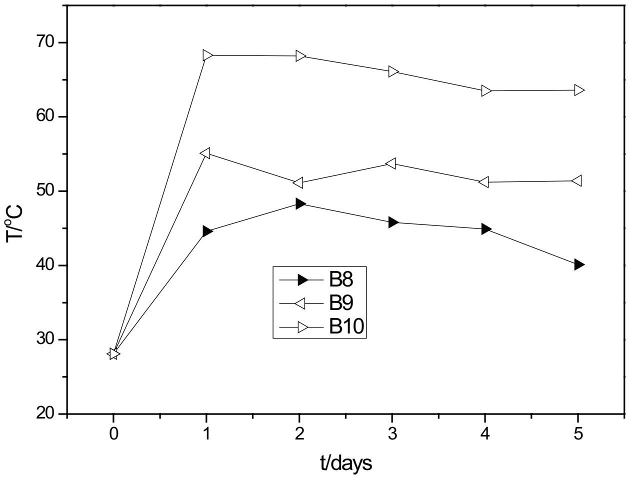

Fig. 5. Changes of temperature of the matrix during the SS and sawdust composting processes under different temperature levels in the bench-scale trials.

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