Journal of Hazardous Materials B124 (2005) 165–172

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Process kinetics of inoculation composting of municipal solid waste

Beidou Xi *, Guojun Zhang *, Hongliang Liu

Chinese Research Academy of Environmental Science, Beijing, 100012, PR China

Received 25 September 2004; received in revised form 11 January 2005; accepted 28 April 2005
Available online 14 June 2005

Abstract

A method was used to improve the composting efficiency by seeding with Inoculum A (*a blend of Bacillus azotofixams*, *Bacillus megaterium* and *Bacillus mucilaginosus*), Inoculum B (a blend of effective cellulolytic strains, i.e. *Trichoderma koningii*, *Streptomyces cellulosae*, and White-rot fungi), and Inoculum C (a mixture of Inoculum A and Inoculum B). There were four runs: the control run (not inoculated), Run A, Run B and Run C. During the runs, parameters such as temperature, O_2, CO_2 and H_2S emissions, and microbial concentration were investigated to study the efficiencies of inoculation composting. The maximum oxygen uptake rates in the control run, Run A, Run B and Run C were calculated as 0.22, 0.32; 0.28 and 0.34 mol/h kg while the corresponding total O_2 quantities accumulated were 511.18, 684.57, 659.74 and 778.47 g/h kg, respectively. In addition, odorous gases were highly reduced by inoculation. In order to understand the mechanisms of inoculation composting process, two stages kinetics equations were developed from the viewpoint of microbial kinetics. These equations showed that, in the first stage, microbial concentration was the main limiting factor of the degradation rate. The degradation rates in control, Run A, Run B and Run C were 10.5, 13.61, 13.08, and 15.671 g/kg h, respectively. In the second stage, the degradation rate was mainly affected by substrate concentration. Although the degradation rates were at almost the same level for both with and without inoculation, inoculation could reduce the half velocity coefficient K_m and in turn stabilize the composting products efficiently. Therefore, inoculation could improve the efficiency of the composting process.

Keywords: Municipal solid waste (MSW); Inoculation composting; Two-stage kinetics equations

1. Introduction

Municipal solid waste (MSW) composting is the decomposition of MSW with a variety of microorganisms, which utilize the organic matter as a carbon source, to make an earthy, dark, crumbly substance that is excellent for adding to houseplants or enriching garden soil [1]. The composting process always occurs in nature, however, many artificial measures have been developed to improve composting efficiency. Over the past decades, effective inoculation has been reported by several researchers [2–6]. Various specialized inocula have been applied in practice. For example, Hatakka [7] studied lignin-modifying enzymes from selected white-rot fungi and found that white-rot fungi played an important role in lignin degradation. Nakasaki [8] reported that a thermophilic bacterium, *Bacillus licheniformis*, could effectively decompose protein and prevent the drop of initial pH values during composting; thus, it could stimulate proliferation of other thermophilic bacteria. Ohtaki [9] revealed that inoculations could increase the microbial population, formulate beneficial microbial communities, improve microbiological quality and generate various desired enzymes; and thus enhance the conversion of organics and reduce odorous gas emissions. The Studies of Lei [10] indicated that the inoculated microbial populations and indigenous populations would evolve continuously, leading to variations during different composting stages. This could result in difficulties in describing the relevant inoculation mechanisms. It also indicated that inoculation did not significantly raise the rate of temperature increase, but did increase the time the composting high temperature remained. Shin et al. [5] also studied the enhancement of composting efficiency by adding

* Corresponding authors. Fax: +86 10 84913946.
E-mail addresses: xibeidou@263.net (B. Xi), zhangguojunmh@yahoo.com (G. Zhang).

0304-3894/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2005.04.026

Nomenclature

A_v	the available surface area per unit volume
k	the maximum rate of solid substrate hydrolysis which occurs at high microbial concentration
K_m	Michaelis ($kg\,m^{-3}$)
K_x	the half velocity coefficient (equal to the microbial concentration when $dS/dt = v/2$)
S	the soluble faction substrate concentration ($g\,kg^{-1}\,h$)
t	composting time (h)
v	the hydrolysis rate of solid substrate
X	the microbial concentration ($g\,kg^{-1}\,h$)
V_m	the maxum degradation rate ($g\,kg^{-1}\,h$).

solid and liquid inoculants. However, the inoculation efficiency was usually affected by competition with indigenous microorganisms. The composting system may not have the desired performance due to improper process operations. For instance, Steven Donald Thomas [11] completed a study on microbial inoculation with mixed cultures of *Bacillus*# 21415 & *Bacillus* sp.#21522, *Trichoderma reesei* QM9414 and *Trichoderma harzianum* FP108 in composting fish wastes. The inocula, performed well overall but were not always significantly better than the controlled compost piles, depending on the season and combination of inocula.

Efforts were also made in developing dynamic models for inoculation processes. A majority of researchers use the Monod equation to simulate the growth of inoculated microorganisms during composting processes [12]. Lapid [13] created a model to simulate inoculation of recycled solid waste and to facilitate handling of organic wastes at the north of Metro, Manila in the Philippines. Huang [14] proposed an empirical model for simulating the thermophilic composting process for vegetable wastes. Bari et al. [15] conducted a series of kinetics analyses on composting processes that were operated under various aeration modes. More recently, Hiraishi Akira [16] investigated microbial dynamics during the start-up of flowerpot, using fed-batch reactors for biodegrading household wastes. Pelaez et al. [17] developed a solid phase kinetic assay for the determination of enzyme activities during a composting process.

Generally, previous studies indicated that the inoculated microbial populations and indigenous populations would keep evolving continuously, leading to variations during different composting stages. To deal with such a problem, it is necessary to divide the composting process into multiple stages, with detailed analyses being carried out at each individual stage. However, there has been a lack of studies in this field. For example, little effort has been made to examine the kinetics of inoculation processes within a multi-stage context. It is thus desired that research in this emerging area be advanced.

The microbial flora and the microbial concentration during the MSW inoculation composting process change over time [9]. The living environment of microorganisms is also incessantly changing with the increase of metabolite production and biochemical reaction. At the beginning of composting, the organic matter concentration is high enough while the microbial community is limited. Thus, seeding with various inocula, i.e., increasing the microbial concentration, is helpful to composting at this stage. As the composting process takes place, the organic matter concentration decreases gradually while the microorganism concentration increases. In this case, the metabolic heat is too low to maintain composting temperature, which causes the drop in oxygen uptake rate. Hereafter, the composting process turns into a stage where the concentration of substrate becomes the limiting factor. Because of the existence of two clearly different stages, it is indispensable to understand the kinetics corresponding to these stages, when investigating the efficiency of inoculation. Nandi et al. [18] studied the microbial synthesis of humus from rice straw. It indicated that rice straw was converted into compost having high content of humic substances, following a two-step composting process. The first step involved degradation of rice straw by selected lignin degrading fungi, *polyporus versicolor, Phanerochaete chrysosporium and Ganoderma eucidum*. The second step involved humification by a general composting process. However, there is little literature to report the variations between the different stages in the inoculation composting process. This may cause some difficulties in determining the efficiency of inoculation composting practically.

The purpose of this study was to determine the effects of seeding inocula during the composting process. Meanwhile, to better understand the kinetics of inoculation composting, two-stage kinetics equations were developed by combining the intrinsic rate equations with fundamental microbial kinetics. In this study, maximum degradation rate and half velocity coefficient were used to determine the effects of different inocula on the composting efficiency.

2. Materials and methods

2.1. Composting materials

MSW was obtained from a typical community in Beijing, China. Samples were sorted and mixed with sawdust, which was used as a bulking agent. Other procedures of feedstock preparation are as follows: (1) adjustment of moisture content to desirable levels based on analysis of the characteristics of the individual raw materials, (2) modification of C/N ratio to a proper level without excessive change of moisture content, and (3) preservation of the composting structure in adequate pore spaces. The characteristics of the materials for composting experiments are shown in Table 1.

The organic matter content was about $600\,g\,kg^{-1}$. The moisture contents (MCs) of the initial waste mixtures for

Table 1
The characteristics of composting materials at the beginning

Samples	Analyses									
	Organic C	Water content ($g\,kg^{-1}$)	Dry matter ($g\,kg^{-1}$)	Ashes ($g\,kg^{-1}$)	Organic matter ($g\,kg^{-1}$)	Total N ($g\,kg^{-1}$)	Total P ($g\,kg^{-1}$)	Total K ($g\,kg^{-1}$)	Total C/N	pH
MSW	300	700	300	300	600	11–14	4.5	2.5	20–30	6.8
Sawdust	430	80	900	100	850					

all tests were adjusted to about 550 $g\,kg^{-1}$ by feeding water or bulking agent to the mixture. The carbon–nitrogen ratio (C/N) was 20∼30:1. Inocula A, B and C in aqueous medium were added to each reactor immediately before recording the respective temperatures. The amounts of Inocula A, B and C added to reactor were 20 $g\,kg^{-1}$. Inoculum A was made by mixing microorganisms that substantially biodegrade easily decomposed organic substrates, such as *Bacillus azotofixams*, *Bacillus megaterium* and *Bacillus mucilaginosus*. Inoculum B was made by mixing the cellulolytic strains and white-rot fungi that strongly biodegrade cellulose and lignin substrates, i.e. *Trichoderma koningii*, *Streptomyces cellulosae*. Inoculum C was produced by mixing Inocula A and B at a ratio of 1:1. The characteristics of inoculants A, B, and C are listed in Table 2.

2.2. Composting reactor and method

A self-made composting reactor with a volume of 34 l was used in this study [19]. A schematic diagram of the reactor is shown in Fig. 1. This reactor was wrapped with 10 cm thick polyurethane layer for heat insulation. Air was provided by an air pump and routed through a perforated PVC tube and an air flow meter. Airflow rate was adjusted at 4.0–6.0 l/min by turning on and off the pump intermittently. The oxygen concentration of the outlet gas was maintained within a range of 100–180 $g\,kg^{-1}$. A precise temperature sensor was used for temperature measurements. An O_2–H_2S monitoring instrument (Model MD-520E) and a CO_2 analyzer (Model LX-710) were used to determine the gases emitted from the reactor. The composting materials were homogenized before being put into the reactor and were manually turned over and sampled once per day. The weight, pH, and MC were measured and recorded everyday. The MC was adjusted by mixing sawdust or distilled water to maintain the optimal range of 450–600 $g\,kg^{-1}$.

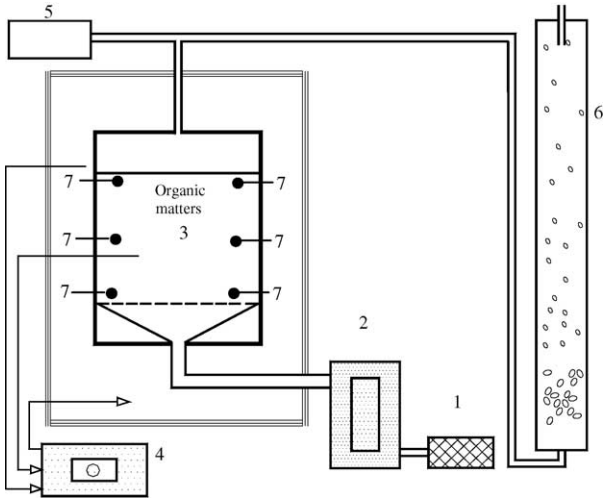

Fig. 1. Schematic diagram of experimental reactor: (1) gas pump; (2) gas flow meter; (3) composting tank; (4) temperature maintainence box; (5) gas analyzer; (6) filter.

2.3. Analytical procedures

Samples taken from six places of the reactor were assembled, mixed and sieved through a 4 mm mesh screen. The amount of dry matter was determined by drying two samples at 105 °C for 12 h in parallel. Total nitrogen (TN), total organic carbon (TOC) and pH were determined in water extracted (volume ratio 1:5) from samples after shaking for 2 h. TN in the mixtures was measured by the Kjeldahl method and samples were pretreated with sulfuric acid. A TOC analyzer (O.I.Analytical Model 1010, College Station, Texas) was used to determine the TOC.

The number of microorganisms was determined by the plate counting method as described by Strom [20]. Actinomycetes, and fungi were isolated on the agar plates by dilution plating. Mesophilic and thermophilic microbial strains were obtained by plating samples taken from composting pro-

Table 2
Characteristics of seed inoculums

Microorganisms	Microorganisms	Inoculum A	Inoculum B	Inoculum C
Bacteria	CFU (30 °C growth)	2.5×10^{11}	1.6×10^{7}	1.8×10^{11}
	CFU(60 °C growth)	6.3×10^{9}	7.5×10^{8}	5.6×10^{9}
Fungi	CFU(30 °C growth)	ND	1.5×10^{6}	1.2×10^{6}
Actinomycetes	CFU(60 °C growth)	ND	5.6×10^{9}	4.5×10^{9}

CFU: colony forming unit (cfu/ml medium); ND: not detected.

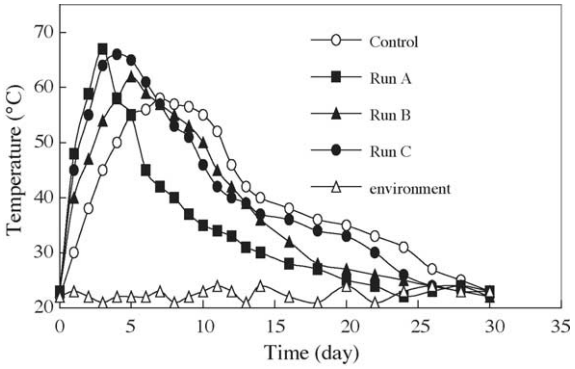

Fig. 2. Temperature profile during the composting processes.

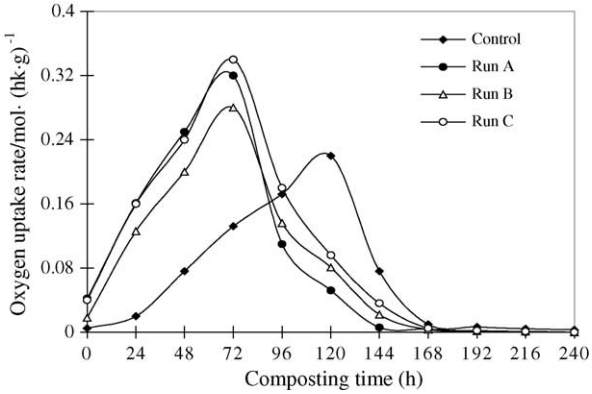

Fig. 3. Oxygen uptake rate profile during the composting processes.

cesses and cultivating the plates at 30 and 60 °C, respectively. Mesophiles and thermophiles were isolated and maintained on trytone soy agar (TSA) and peptone agar (PA), respectively. Isolates were obtained by streaking out all the colonies of a spread plate within a sector containing 40 colonies. Oxygen uptake rate and CO_2 conversion rate were calculated according to the outlet gas concentrations.

3. Results

3.1. Temperature profile

Temperature profiles for the four experiments and the ambient temperature are illustrated in Fig. 2. The ambient temperature only fluctuated within a very narrow range (around 22 °C) during the composting period. However, the composting temperatures rose up gradually after the moisture content was adjusted to around 550 g kg^{-1} and air flow was introduced. Metabolic heat was generated due to the degradation of readily degradable organic matter. The temperature in the control experiment increased to a peak of about 58 °C at day 5 and remained at a peak temperature for about 5 days (thermophilic stage). The temperatures dropped thereafter and remained at a lower level from day 10 to 25 (cooling stage) and then further dropped to the ambient temperature from day 25 to 50 (maturing stage). Although the temperature profiles of inoculation composting processes were similar to those of conventional non-inoculated composting (control), the peak temperature and the rate of increase during the thermophilic stage were different. For Run A, the peak temperature could be reached in five days. In Run B and Run C, the peak temperatures could be reached in 10 and 8 days, respectively.

3.2. Emission of outlet gas

H_2S, CO_2 and O_2 variations were used to determine the degradation rates during the composting processes under different conditions [21]. Table 3 shows the variations of H_2S, CO_2 and O_2 concentration with time in the outlet gas.

As shown in Table 3, the maximum concentrations of H_2S emission were 30, 10, 5, 4 ppm in the control run, Runs A, B and C, respectively. Furthermore, H_2S emission lasted for the longest time in the control run. These results indicated that inoculation was helpful in controlling H_2S emission.

The profiles of oxygen uptake rate and accumulative oxygen consumption for the four experiments are presented in Figs. 3 and 4, respectively. The maximum oxygen uptake

Table 3
Emission of gas in outlet

Time (day)	Emission of oxygen (ml l^{-1} O_2)				Emission of carbon dioxide (ml l^{-1} CO_2)				Emission of H_2S (ml l^{-1})			
	Control	Run A	Run B	Run C	Control	Run A	Run B	Run C	Control	Run A	Run B	Run C
0	209	209	209	209	0	0	0	0	0	0	0	0
24	202	142	162	143	7	54	418	58	0	0	0.5	1.0
48	172	104	134	119	33.6	31.8	68.5	982	0	0.3	1.0	4.0
72	159	78.3	104	82	45	119	95.0	111	30	10	5	3.2
96	145	168	158	142	58.2	37.1	60.1	65	28	8.2	4.8	2.8
120	126	190	179	173	75.5	18.2	29.1	27.5	20	6.5	3.3	1.9
144	181	207	201	196	29.2	6.4	5.5	13.0	15.4	4.3	2.0	0.5
168	202	208	208	207	12.0	5.4	4.5	2.7	12.1	2.2	1.0	0.2
192	206	209	208	208	7.4	4.1	3.6	1.8	7.4	1.1	0.4	0
216	207	209	209	209	5.6	0.3	3.5	1.0	2.3	0.5	0.1	0
240	208	209	209	209	1.0	0.0	0.5	0.3	0.6	0	0	0

Aeration flow was 1.0 l/(min kg), the moisture of composting matters was around 550 g kg^{-1}.

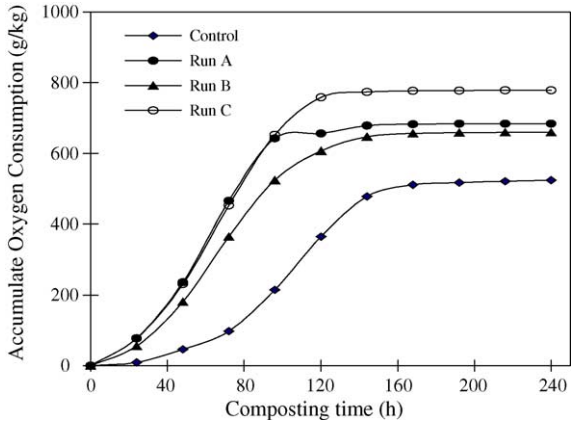

Fig. 4. Oxygen accumulated profile during the composting processes.

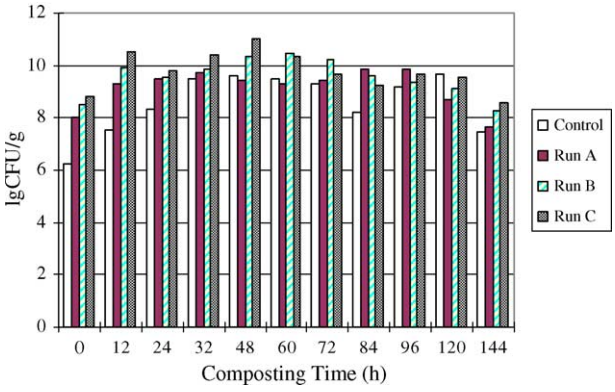

Fig. 6. Total heterotroph counts profile in composting.

rates in the control run, Run A, Run B, Run C were 0.22, 0.32, 0.28 and 0.34 mol/h kg while the corresponding total quantities accumulated were 511.18, 684.57, 659.74 and 778.47/h kg, respectively. These results suggested that inoculation improved the MSW degradation rate, especially in Run C.

Fig. 5 shows the CO_2 conversion rates over composting time. It was found that the CO_2 concentration in the compost was strongly dependent on the inoculum used. The CO_2 conversion rate reached up to 0.30 mol/(h kg) in Run C while the peak CO_2 conversion rate was only 0.20 mol/(h kg) in the control run. These results suggested that biological activity in Run C was highest since CO_2 conversion rate is usually considered as an indicator of the respiratory activity of the compost micro flora.

3.3. Total heterotroph counts

To investigate the effects of inocula on composting processes, total heterotroph counts in the composting system were examined. The total heterotroph counts profiles are shown in Fig. 6.

The total microorganism populations in Run A, Run B and Run C were much higher than those in the control run. At the beginning of the composting, the $\log_{10}$CFU (colony forming units) g^{-1} varied from 6.0 to 9.0 in the control run, Run A, Run B and Run C (Fig. 6). The corresponding peak $\log_{10}$CFU values were 9.0 (at day 7), 10 (at day 2), 9.5 (at day 4), and 10 (at day 3). This suggested that inoculation composting would require a shorter time to reach the maximum population compared with conventional non-inoculated composting.

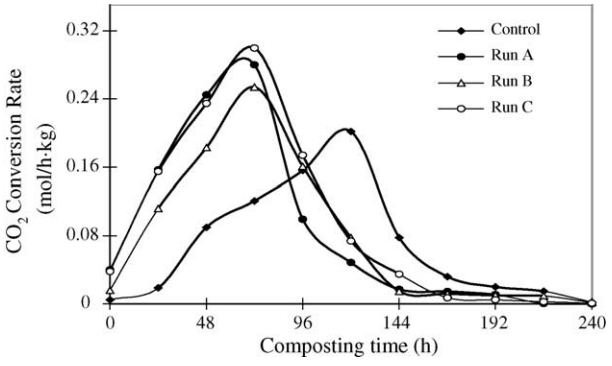

Fig. 5. CO_2 conversion rate profile during the composting processes.

3.4. Two-stage microbial kinetics of the inoculation composting

There are two different stages in terms of the limiting factors in the inoculation composting process. At the beginning, enough organic matter was sufficient to be decomposed while the microbial population was insufficient and in turn limiting the composting process. With the process ongoing, the organic matter concentration decreased while the microbial populations increased. When the metabolic heat was insufficient to maintain composting temperature and the oxygen uptake decreased, the substrate became the main limiting factor of the composting process. Based on the above analysis, two-stage kinetics equations derived from the intrinsic rate equations and fundamental microbial kinetics were developed and then used to examine the efficiency of inoculation composting process. The first stage, from the beginning to the peak of the oxygen uptake rate, was controlled by microbes concentration. The second stage, from the peak oxygen uptake rate to the end, was controlled by substrate concentration. These two stage kinetics equations are helpful to better understand the composting rate and microbial activity in the inoculation composting process. In the following, the equations for the two-stage kinetics are presented.

In the first stage, the degradation rate follows the following expression. The degradation rate was a function of the microbial concentration for a heterogeneous system with solid substrate [22]:

$$v = -\frac{\mathrm{d}S}{\mathrm{d}t} = \frac{kA_v X}{K_X + X} \quad (1)$$

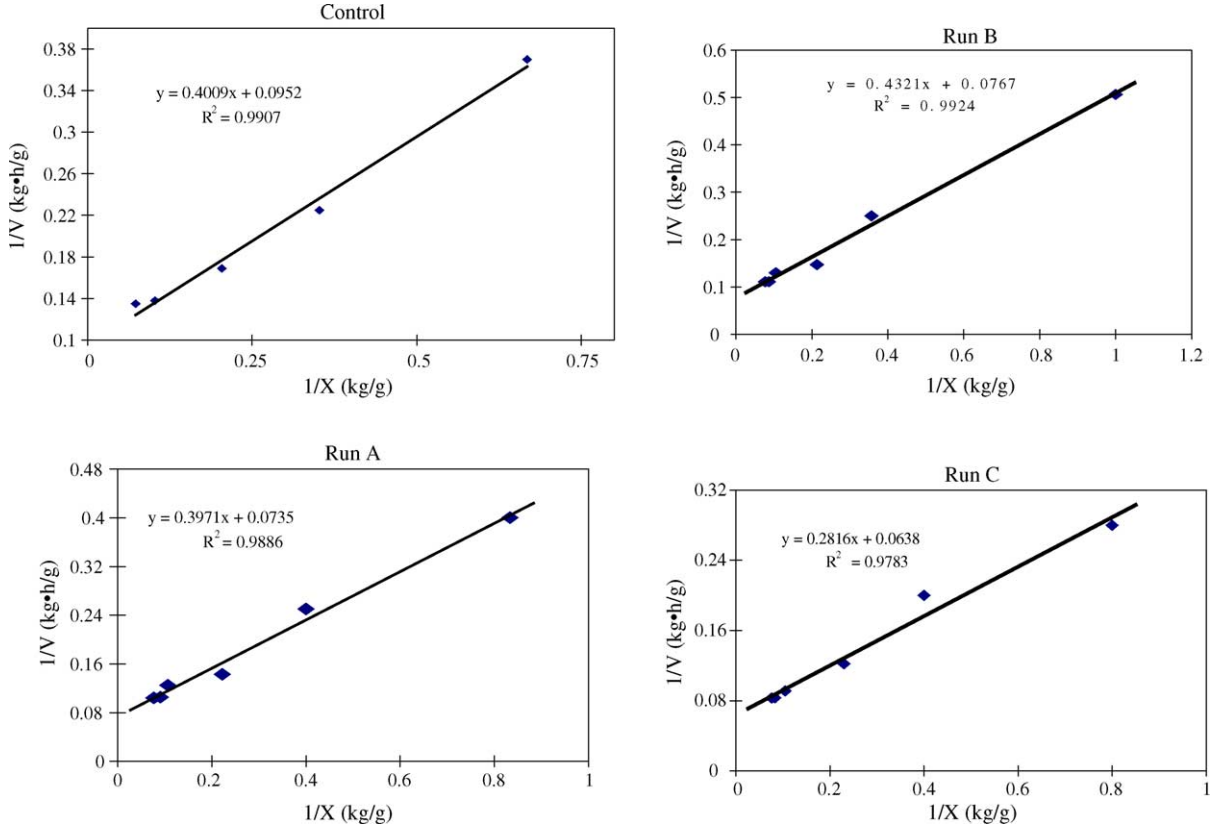

Fig. 7. [1/*V*] vs. [1/*X*] in the first stage.

where v is the organic matter degradation rate ($g\,kg^{-1}\,h$), dS/dt the hydrolysis rate of soluble faction, S the soluble faction concentration ($g\,kg^{-1}\,h$), t the composting time (h), X the microbial concentration ($g\,kg^{-1}\,h$), k the maximum rate of soluble faction substrate hydrolysis which occurs at high microbial concentration, K_X the half velocity coefficient (equal to the microbial concentration when $ds/dt = v/2$), and A_v is the available surface area per unit volume.

From Eq. (1), we have

$$\frac{1}{v} = \frac{K_X}{kA_V}\frac{1}{X} + \frac{1}{kA_V} = \frac{K_X}{V_m}\frac{1}{X} + \frac{1}{V_m} \tag{2}$$

where V_m is the maximum degradation rate ($g\,kg^{-1}\,h$)

In the case of the control run, the values of $1/V_m$ (0.0952) and K_x/V_m (0.4009) were derived from the regression equation ($y = 0.4009x + 0.0952$). Therefore, V_m and K_x could be calculated as10.504 and 4.21, respectively. Putting V_m and K_x values into Eq. (2), Eq. (3) was developed as follows. Similarly, coupled with Fig. 7, the following kinetic equations regarding degradation rates of Run A, Run B and Run C can be developed as Eqs. (4)–(6):

$$V_{\text{Control}} = \frac{10.504X}{4.21 + X} \tag{3}$$

$$V_{\text{Run A}} = \frac{13.61X}{5.403 + X} \tag{4}$$

$$V_{\text{Run B}} = \frac{13.038X}{5.63 + X} \tag{5}$$

$$V_{\text{Run C}} = \frac{15.67X}{4.41 + X} \tag{6}$$

In the second stage, the degradation rate can be described as a function of the substrate concentration, which is given by

$$V = \frac{V_m S}{K_m + S} \tag{7}$$

$$\frac{1}{V} = \frac{K_m}{V_m}\frac{1}{S} + \frac{1}{V_m} \tag{8}$$

Similarly, coupled with Fig. 8, the second stage kinetic equations of the control run, Run A, Run B, and Run C were obtained as follows:

$$V_{\text{Run A}} = \frac{7.73S}{204.95 + S} \tag{9}$$

$$V_{\text{Run B}} = \frac{7.65S}{186.41 + S} \tag{10}$$

$$V_{\text{Run C}} = \frac{7.26S}{154.25 + S} \tag{11}$$

$$V_{\text{Control}} = \frac{7.71S}{214.18 + S} \tag{12}$$

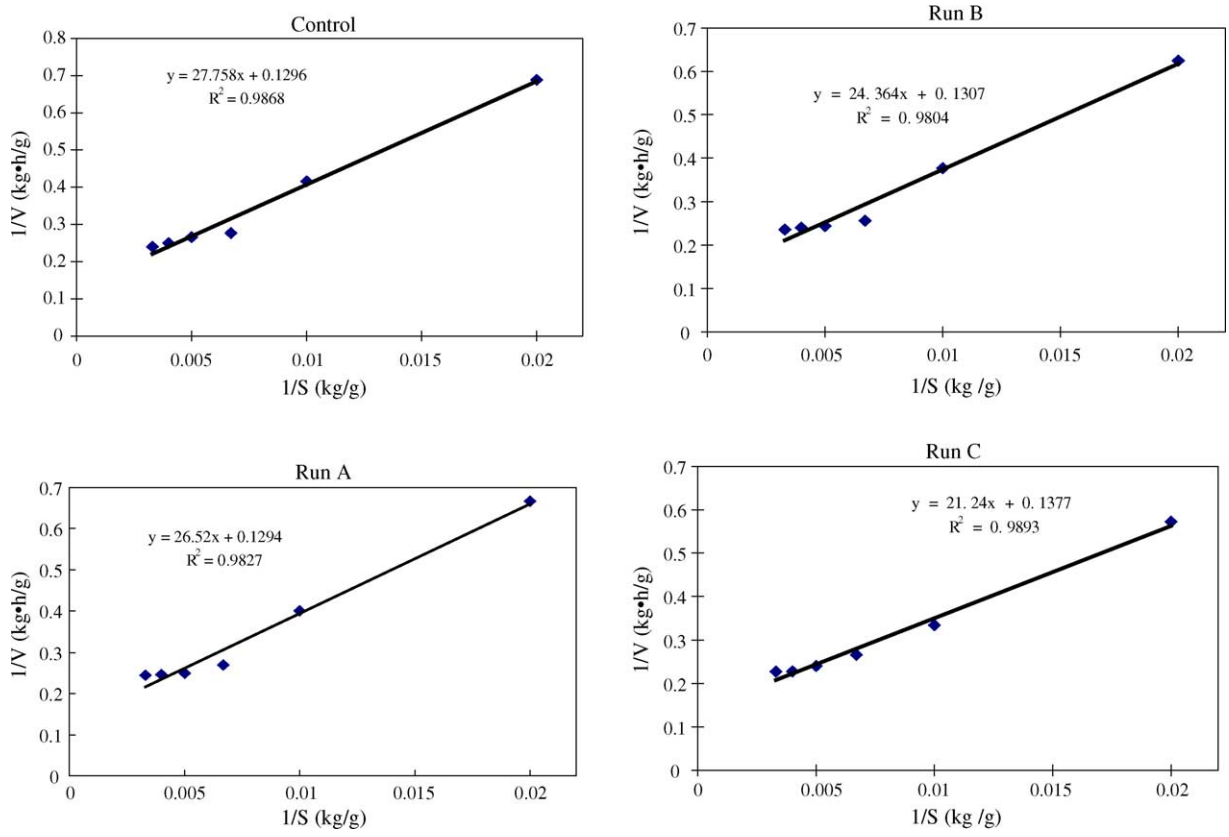

Fig. 8. [1/*V*] vs. [1/*S*] in the second stage.

4. Discussion

Although most organic wastes are decomposed by the indigenous microbial flora [23], this does not mean that microbes concentration is a limiting factor, particularly in the first stage of the composting process. In terms of Eqs. (3)–(6), unless $X \gg K_X$, the degradation rate could be improved with the increase of the microbial concentration (X). It was noted that inoculation would be an effective way to improve the microbial concentration and in turn increase the composting rate. In addition, by inoculating complex microorganisms, maximum degradation rates, KA_v, would improve due to the high bioactivity of inoculum. For instance, KA_v varied from 10.5, 13.61, 13.08, to 15.671 g/kg h in the control run, Run A, Run B, and Run C, respectively. Since inoculum C was a mixture of inoculum A and inoculum B, which had a sufficient and wide variety of microbes, the maximum degradation rate in Run C was improved highly and the corresponding value was the highest. It was also noted from Fig. 2 that in the first 4 days, the temperatures in Run A were higher than those in the control run, Run B and Run C. This may be because inoculum A contained a large quantity of microorganisms, which could quickly decompose soluble and biodegradable organic matter such as mono-saccharides, starch, lipids and proteins, and increase the temperature up to a high value in a short time. After this period, the temperature of Run A rapidly dropped to below 40 °C. This suggested that the seed in Run A could not persist in for a long time although it was efficient for the start-up of composting. Compared to Run A, the peak temperature in Run B was lower than that in Run A. Moreover, it took a longer time to reach the high temperature. As a comparison, in Run C, the inoculum of complex microorganisms including inoculum A and B could not only reach a relatively high temperature but also maintain the high temperature for a relatively long time. In the conventional composting process, the temperature of the composting system increases slowly with an obvious delay period, especially at the initial stage of batch operations [24]. During the delay period, a lot of odorous gases such as H_2S and NH_3 were produced due to the high moisture content, oxygen availability, and low temperature. It was noted from this study that the delay period could be effectively shortened by inoculating using proper microorganisms.

As outlined earlier, as the composting goes on, the soluble substrates become less, thus, the substrates may become the significant limiting factor to the degradation rate. At this time, the composting process would change to the second stage. During this stage, biorefractory substrates, such as cellulose fiber and lignin became the main substrates. In our case, KA_v (i.e. V_m) in the control run, Run A, Run B and Run C was 7.73, 7.65, 7.26 and 7.71 g/kg h, respectively. Obviously, the improvement of V_m was insignificant. However, these values were much lower than those in the first stage. This further suggested that the substrate was the main limiting factor dur-

ing the second stage. Usually, K_m value is an indicator of the composting products stability. The lower the K_m, the more stable the composting products. From Eqs. (9)–(12), inoculation could reduce the half velocity coefficients K_m which were 214.18, 204.95, 186.41, and 154.25 g/kg in the control run, Run A, Run B, and Run C, respectively. These results indicated that inoculum containing cellulolytic strains, White-rot fungi (in Run B and Run C) could efficiently stabilize the composting process. In particularly, inoculum C was the most efficient because the compost of Run C contained a large number of inocula A and B, whose bioactivities were higher than those of the indigenous microorganism or inoculum A or inoculum B.

5. Conclusion

A composting process by seeding with an inoculum containing *B. azotofixams*, *B. megaterium*, *B. mucilaginosus*, cellulolytic strains, and White-rot fungi was found viable for improving the composting efficiency. Two-stage kinetics equations were developed to explain the inoculation composting process. In the first stage, the composting process was limited by microbial concentration, thus, the degradation rate could be improved effectively by seeding inocula. Meanwhile, odorous gases were also controlled well since the delay period could be shortened. In the second stage, inoculation could reduce the half velocity coefficient K_m and in turn to stabilize the composting products and improve the composting quality. In conclusion, seeding inoculum containing *B. azotofixams*, *B. megaterium*, *B. mucilaginosus*, cellulolytic strains, and White-rot fungi was very efficient in accelerating degradation rate, reducing odorous gas emissions and stabilizing composting products.

Acknowledgments

This study was supported by the National Hi – Tech R@D Program (973) of China (2002CB410800-7) and No. 2002CB412302, and the National “863” of China (No. 2002AA601012). We would like to extend our thanks to Mr. Chu Shen Chee, Patrick for helping us to correct the written English.

References

[1] M.F. Hamoda, H.A. Abu Qdais, J. Newham, Evaluation of municipal solid waste composting kinetics, Resour. Conserv. Recycl. 23 (4) (1998) 209–223.
[2] E.M. Biey, H. Mortier, W. Verstraete, Nitrogen transfer from grey municipal solid waste to high quality compost, Bioresour. Technol. 73 (2000) 47–52.
[3] A.C. Gaur, K.V. Sadasivam, R.S. Matthur, S.P. Magu, Role of mesophilic fungi in composting, Agric. Wastes 4 (1982) 453–460.
[4] R.S. Matthur, S.P. Magu, K.V. Sadasivam, A.C. Gaur, Accelerated compost and improved yield, Biocycle 27 (1986) 42–44.
[5] H.S. Shin, E.J. Hwang, B.S. Park, T. Sakai, The effects of seed inoculation on the rate of garbage composting, Environ. Technol. 20 (1999) 293–300.
[6] H. Baheri, P. Meysami, Feasibility of fungi bioaugmentation in composting a flare pit soil, J. Hazard. Mater. 89 (2-3) (2002) 279–286.
[7] A. Hatakka, Lignin-modifying enzymes from selected white-rot fungi:production and role in lignin degradation, FEMS Microbiol. Rev. 13 (1994) 125–135.
[8] K. Nakasaki, S. Fujiwara, H. Kubota, A newly isolated thermophilic bacterium, *Bacillus licheniformis* HA1 to accelereate the organic matter decomposition in high rate composting, Compost Sci. Utilization 2 (1994) 88–96.
[9] F. Lei, J.S.V. Gheynst, The effect of microbial inoculation and pH on microbial community structure changes during composting, Process Biochem. 35 (2000) 923–929.
[10] A. Ohtaki, N. Akakura, K. Nakasaki, Effects of temperature and inoculum on the degradability of poly-ε-caprolactone during composting, Polym. Degrad. Stab. 62 (1998) 279–284.
[11] Steven Donald Thomas, A Compost study: a critical evaluation of microbial inoculation in composting fish wastes, Master Thesis of Science in Environmental Studies, Bemidji State University, 1995.
[12] P. Agamuthu, Looi Chee Choong, Shameem Hasan, V.V. Praven, Kinetic evaluation of composting of agricultural wastes, Environ. Technol. 21 (2) (2000) 185–192.
[13] Danilo G. Lapid, Chtistopher C. Ancheta, Theresa J. Villareal, Biocycle international – the Philippines – creating a Model to recycle solid waste, Biocycle 40 (12) (1999) 72–73.
[14] Ju-Sheng Huang, Chun-Hung Wang, Charng-Gwo Jib, Empirical model and kinetic behavior of thermophilic composting of vegetable waste, J. Environ. Eng. 126 (11) (2000) 1019–1026.
[15] Quazi H. Bari, Albert Koenig, Tao Guihe, Kinetic analysis of forced aeration composting—Reaction rates and temperature, Waste Manage. Res. 18 (2000) 303–312.
[16] Hiraishi Akira, Narihiro Takashi, Yamanaka Yosuke, Microbial community dynamics during start-up operation of flowerpot-using fed-batch reactors for composting of household biowaste, Environ. Microbiol. 5 (9) (2003) 765–776.
[17] C. Pelaez, A. Mejia, A. Planas, Development of a solid phase kinetic assay for determination of enzyme activities during composting, Process Biochem. 39 (8) (2004) 971–975.
[18] N. Nandi, J.N. Hajra, N.B. Sinha, Microbial synthesis of humus from rice straw following two-step composting process, J. Indian Soc. Soil Sci. 44 (3) (1996) 413–416.
[19] B. Xi, H. Liu, Composting MSW and sewage sludge with effective complex microorganisms, J. Environ. Sci. 14 (2) (2002) 264–268.
[20] P.F. strom, Effect of temperature on bacterial species diversity in thermophilic solid-waste composting, Appl. Environ. Microbiol. 50 (4) (1985) 899–905.
[21] Y. Eklind, H. Kirchmann, Composting and storage of organic household waste with different litter amendments. I. carbon turnover, Bioresour. Technol. 74 (2000) 115–124.
[22] R.T. Haug, Development of simulation models, in: The Practical Handbook of Compost Engineering, Lewis Publishers, 1993, pp. 342–436.
[23] M. Tuomela, M. Vikman, A. Hatakka, M. Itävaara, Biodegradation of lignin in a compost environment: a review, Bioresour. Technol. 72 (2000) 169–183.
[24] S.M. Tiquia, N.F.Y. Tam, I.J. Hodgkiss, Effects of bactierial inoculum and moisture adjustment on composting of pig manure, Environ. Pollut. 96 (2) (1997) 161–171.