Journal of Industrial Microbiology & Biotechnology (2001) 27, 67–71

www.nature.com/jim

Oxygen-limited decomposition of food wastes in a slurry bioreactor

JI Park, Y-S Yun and JM Park

Environmental Biotechnology Laboratory, Department of Chemical Engineering, School of Environmental Science and Engineering, Pohang University of Science and Technology, San 31, Hyoja-dong, Pohang, Kyungbuk 790-784, South Korea

The slurry bioreactor system is an effective means for treating highly saline food wastes, which may not be recycled as composts. The effect of aeration rate was investigated in a slurry bioreactor as a major factor affecting the slurry-phase decomposition of food wastes. The aeration rate affected significantly the decomposition performance and the composition profiles of the liquid and solid phases. The decomposed carbon was almost linear with oxygen consumption, indicating that the slurry-phase decomposition of food wastes was limited by oxygen transfer. The oxygen requirement for decomposing 1 g organic carbon in food wastes was estimated to be 61.5 g O_2. *Journal of Industrial Microbiology & Biotechnology* (2001) **27,** 67–71.

Keywords: food wastes; decomposition; slurry bioreactor; aerobic degradation; composting

Introduction

Food wastes have been treated by such methods as landfills, incineration, recycling for use as compost or animal feed, and complete decomposition [5]. Although widely used for their simplicity, landfills have been confronted with some critical problems such as lack of dumping sites and water pollution by leachates. Incineration use is also restricted because of the expensive operating cost and air pollution [2]. Sanitary problems as well as lack of nutrients limit recycling of food wastes as animal feeds [5]. Composting of food wastes has been considered as an attractive means since value-added products can be obtained from wastes. However, food wastes containing high salt concentrations (e.g., Korean food wastes) are not suitable substrates for compost [6].

In Korea, therefore, increasing attention has been given to reducing organic matter in food wastes *via* high-rate decomposition. In this method, the decomposition rate is accelerated by optimizing the operating conditions of the conventional composting process such as temperature and aeration rate [7,8,10,11,15]. Recently, we proposed that a slurry bioreactor system was effective for decomposition of food wastes compared to the conventional solid state composting system [17]. However, further studies on optimization of operating conditions are required for the practical application of this system.

In the present work, the effect of aeration rate on the decomposition of food wastes was investigated. The oxygen requirement for the decomposition of food wastes was estimated by using the linear relationship between decomposed carbon and oxygen consumption established from the experimental data.

Correspondence: Dr JM Park, Environmental Biotechnology Laboratory, Department of Chemical Engineering, School of Environmental Science and Engineering, Pohang University of Science and Technology, San 31, Hyoja-dong, Pohang, Kyungbuk 790-784, South Korea
Received 20 September 2000; accepted 29 April 2001

Materials and methods

Food wastes

Food wastes were obtained from a Korean food restaurant on the campus of Pohang University of Science and Technology, Pohang, South Korea. Their composition varied according to the daily menu of the restaurant; therefore, the food wastes were separated and remixed to make the typical composition of Korean food wastes as shown in Table 1 [13]. The water content of remixed food wastes was 80.3% (w/w). The average content of carbon and nitrogen in dried food wastes was 48.4% (w/w) and 6.9% (w/w), respectively. The food wastes were chopped into small pieces (< 1 cm) to minimize errors in sampling. Wet food wastes were used in the experiment, but the weight was described on a dry weight basis.

Microorganisms

A microbial mixture capable of decomposing food wastes in the slurry-phase condition was obtained from many kinds of commercially available composts. Since the environment in the slurry bioreactor is different from that in conventional solid state composting with respect to the water content or activity, the microbial mixture used in this study was adapted to the slurry-phase condition. The detailed procedure for collecting the microbial mixture was described previously [17]. Briefly, various mature composts were incubated in a 500-ml flask containing 200 ml water and 20 g dry weight of food wastes as a substrate on a rotary shaker at 200 rpm and 30°C for 10 days. Thereafter, 50% of the slurry in the flask was removed and 50 g fresh food wastes and 100 ml water were added into the flask every week. By this successive incubation, the microorganisms were acclimated to the new environment of slurry-phase conditions and the resulting slurry was used as an inoculum in the subsequent experiments.

Bioreactor operation

A typical stirred tank reactor was used in this study; the total and working volumes were 2 and 1 l, respectively. The reactor was

Table 1 Composition of food wastes

Food types	Composition (%)
Cereals	16±2
Fruits	14±2
Vegetables	51±2
Meats and fish	19±2

equipped with paddle-type impeller and sparger for agitation and aeration. Food wastes (23.1 g dry weight) and microbial mixture (10 ml) were introduced into the stirred tank reactor. The working volume was then adjusted to 1 l by adding water. In all experiments, agitation speed was 120 rpm and temperature was controlled at 25±2°C. In order to change the oxygen transfer rate, various aeration rates were used, e.g., 0.0, 0.1, 0.3, 0.7, and 1.2 l min^{-1}.

Analytical methods

The oxygen transfer coefficient was determined before commencing the decomposition experiments by using the gassing-in method [12]. This was repeated three times and average values are presented with standard deviations.

Since the working volume of the reactor decreased due to water evaporation, it was adjusted to 1 l by adding water every sampling time. For measuring the compositions of solid and liquid phases, 5 ml of sample was taken from the reactor every 5 days. The sample was centrifuged at 3000 *g* for 10 min. Thereafter, the supernatant was filtered through a 0.2 μm pore size membrane filter (Millipore, Allen, TX) and used to analyze the concentrations of dissolved organic carbon (DOC), nitrate and phosphate. The solid sample was dried in an oven at 105°C for 24 h to measure the dry weight of suspended solids (SS). It should be noted that the SS contained growing microbial biomass as well as food wastes. The dried solid was then homogenized and the elemental composition was measured using an elemental analyzer (CHNS-928; Leco, St. Joseph, MI). Dissolved oxygen (DO) and pH were measured *in situ* by submerging electrodes (Ingold, Woburn, MA) in the slurry reactor. The concentration of DOC was analyzed using a TOC analyzer (5000A; Shimadzu, Kyoto, Japan). Dissolved nitrate and phosphate were measured by an ion chromatograph (DX-120; Dionex, Sunnyvale, CA) as described previously [16].

Results and discussion

Oxygen transfer

In general, the mass transfer in a bioreactor system is characterized quantitatively by the volumetric transfer coefficient, K_La (Figure 1). In this study, an appropriate range of K_La could be obtained by changing the aeration rate at a constant mixing intensity (120 rpm). A broad range of K_La was used up to approximately 1200 h^{-1}, which covered the K_La values achievable in various types of bioreactors. According to a previous report [3], the K_La value of stagnant water with specific surface area of 1 cm is 7.56 h^{-1} and that of bubble columns ranges from 10 to 30 h^{-1}. In agitated fermentors, the K_La value ranges from 325 h^{-1} (agitation speed of 500 rpm) to 1000 h^{-1} (agitation speed of 750 rpm). Therefore, the K_La range (0–1200 h^{-1}) used in this work (Figure 1) was appropriate for the study of aeration effects. The K_La values obtained at different aeration rates were used for calculating the oxygen consumption rate (see *Oxygen Requirement* section).

Typical characteristics of decomposition of food wastes

Figure 2 shows the typical profiles of compositions in the liquid and solid phases during decomposition of food wastes in the slurry bioreactor; the SS concentration was reduced rapidly within 1.5 day at a rate of 6.5 g dry wt l^{-1} day^{-1} (Figure 2). The SS concentration was 16 g l^{-1} in the first sample at 2.5 h, although the concentration in the food wastes initially introduced was 23.1 g l^{-1}. The DOC concentration was as high as 5.2 g l^{-1} (Figure 2B). This was probably due to dissolution of the soluble portion of the food wastes, such as salts, sugars and other soluble ingredients in the food. Appearance of high concentrations of nitrate and phosphate at the first sample, which were not contained in the added water, supported the dissolution of salts when the food wastes were contacted with added water.

The pH decreased after food wastes were introduced to the reactor, possibly due to organic acids produced from decomposition of the food wastes. Following day 2, the pH increased slowly and reached 8.5 at the end of the operation (day 5). During the rapid reduction of SS, DO dropped to near zero, which implied that the oxygen transfer rate was slower than the oxygen consumption rate for the oxidation of food wastes by the microorganisms. After decomposition of almost all the biodegradable matter, including SS and DOC, at approximately day 1.5, DO resumed increasing. The DO change along with the SS reduction suggested that oxygen transfer could be an important factor affecting the decomposition performance of the slurry bioreactor.

Effect of aeration rate on the composition of liquid phase

The aeration rate affected significantly the profiles of DO and pH (Figure 3). When the aeration rate was lower than 0.3 l min^{-1}, the reactor system remained in an anoxic condition during the whole

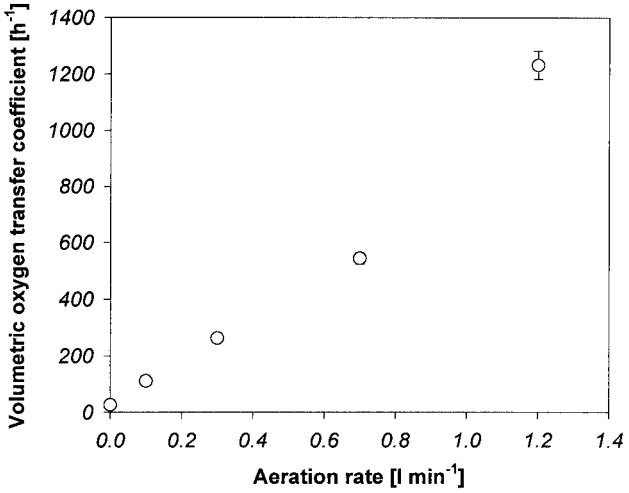

Figure 1 Volumetric oxygen transfer coefficient at various aeration rates. Error bars represent the standard deviations of three replicate experiments.

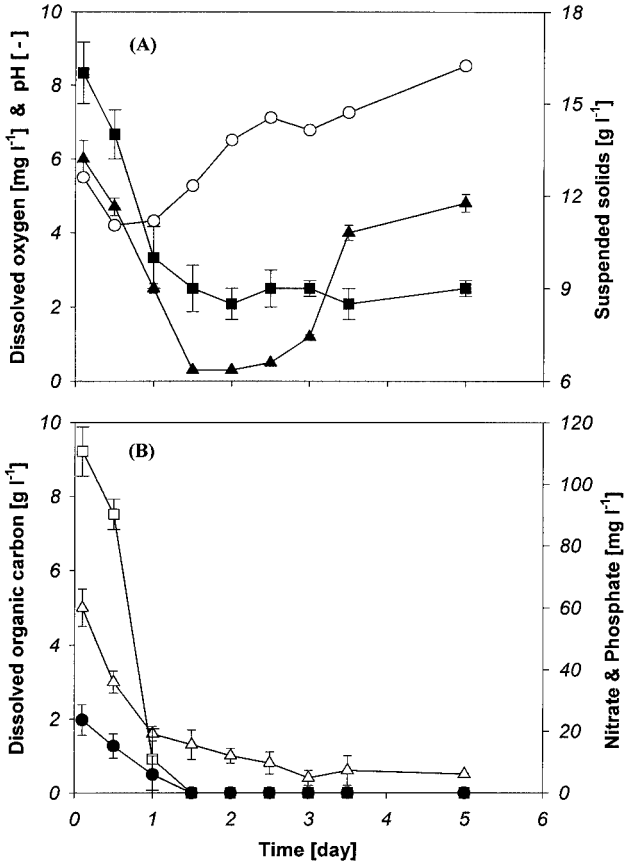

Figure 2 Typical characteristics of decomposition of food wastes in the slurry bioreactor at 0.7 l min^{-1} aeration rate. Error bars represent the standard deviations of three samples. (A) ■, suspended solids; ○, pH; ▲, dissolved oxygen. (B) △, DOC; ●, phosphate; □, nitrate.

operation period. In this range, therefore, the transferred oxygen was completely consumed. By increasing the aeration rate (0.7 and 1.2 l min^{-1}), the profile of DO had a typical pattern in which the DO concentration dropped at the beginning and increased from day 1.5. From day 1.5, the easily biodegradable organic matter was almost decomposed as suggested by the relationship between the time courses of SS (or DOC) and DO (Figure 2).

The change in pH was also affected by the aeration rate (Figure 3). From the beginning, the solution pH was kept lower than pH 5.0 and then began to increase from a certain time depending on aeration rates. The pH began to increase earlier when the aeration rate was higher. In the anoxic condition (no aeration), the pH did not increase but remained between 3.3 and 4.0, presumably because the aerobic microbial reaction consuming organic acids did not occur [1].

Figure 4 shows the residual concentrations of DOC, nitrate and phosphate at day 5. As the aeration rate increased up to 0.3 l min^{-1}, the residual concentration of DOC decreased significantly. When the aeration rate was higher than 0.3 l min^{-1}, the residual DOC was approximately 0.4±0.1 g l^{-1}, which may represent components not easily biodegradable in the slurry bioreactor. Nitrate was not detected at any condition, and phosphate completely disappeared at high aeration rates (Figure 4). This implied that nutrients released from the food wastes were completely consumed by growing microbial cells that were more active at the higher aeration rates.

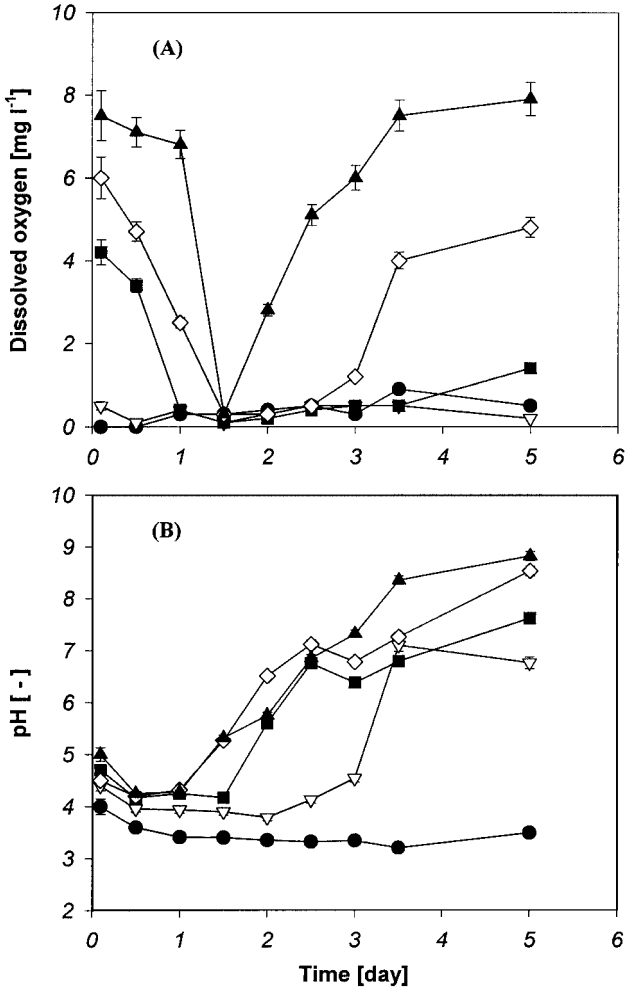

Figure 3 Variations of dissolved oxygen (A) and pH (B) during operation of the slurry bioreactor. Error bars represent the standard deviations of three samples. The aeration rates are 0.0 (●), 0.1 (▽), 0.3 (■), 0.7 (◇) and 1.2 (▲) l min^{-1}.

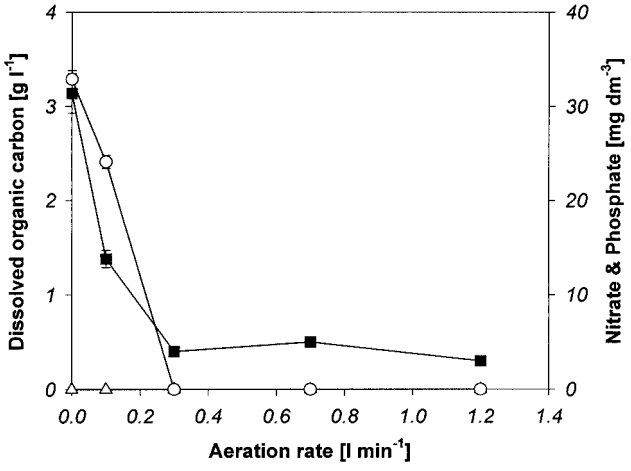

Figure 4 Residual concentrations of DOC (■), nitrate (△) and phosphate (○) after 5-day operation of the slurry bioreactor at various aeration rates. Error bars represent the standard deviations of three samples.

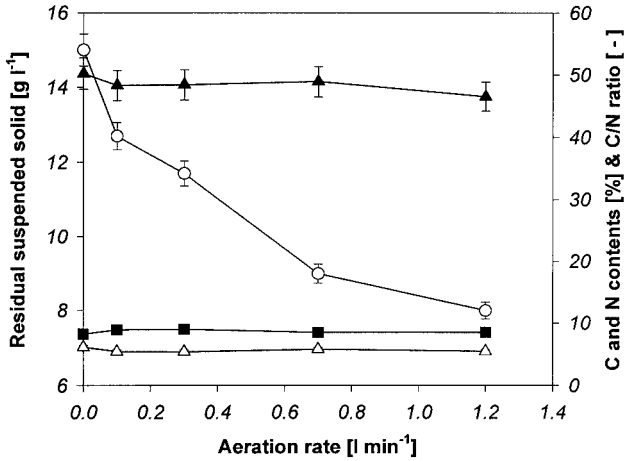

Figure 5 Residual concentration and elemental composition of suspended solids after 5-day operation of the slurry bioreactor at various aeration rates. Error bars represent the standard deviations of three samples. ○, suspended solids; ▲, carbon content; ■, nitrogen content; △, carbon:nitrogen ratio.

Effect of aeration rate on the composition of the solid phase

The composition of the solid phase was examined at day 5 (Figure 5). As the aeration rate increased, the residual SS concentration decreased. However, the aeration rate did not greatly influence the elemental composition of SS. Also, approximately 8.1 g l^{-1} of SS was removed even at the aeration rate of 0.0 l min^{-1}.

Effect of aeration rate on the decomposition of organic carbon

In the slurry bioreactor system, the organic carbon was in part assimilated by the microorganism and oxidized into inorganic carbon (CO_2) by their endogenous respiration. However, the assimilated carbon could not be considered to be "removed" because the microbial biomass remained in the bioreactor. The inorganic carbon that escaped from the bioreactor into the atmosphere is designated as "decomposed carbon."

In order to estimate the decomposed carbon, the carbon balance should be established over the working volume of the reactor. The carbon in the initially introduced food wastes would exist in various forms at a certain time: residual food wastes not to be degraded as yet, dissolved organic matter, microbial biomass to be assimilated, and gaseous inorganic carbon produced by the endogenous respiration:

$$C_{FW}(0) = \{C_{FW}(t) + C_M(t)\} + C_L(t) + C_G(t) \quad (g\,l^{-1})$$

where $C_{FW}(0)$ and $C_{FW}(t)$ are the carbon concentration existing in the food wastes initially and at a certain time, respectively, $C_M(t)$ is the carbon concentration existing in microbial biomass, $C_L(t)$ is the DOC concentration and $C_G(t)$ is the decomposed carbon at a certain time. Since it was not easy to determine $C_{FW}(t)$ and $C_M(t)$ separately, the carbon concentration existing in SS ($C_{SS}(t)$) was measured as a lumped quantity. Therefore, the decomposed carbon can be estimated by using experimentally measurable parameters as follows:

$$C_G(t) = C_{FW}(0) - C_{SS}(t) - C_L(t) \quad (g\,l^{-1})$$

The $C_{FW}(0)$ and $C_{SS}(t)$ were obtained by multiplying dry weights by carbon contents of food wastes and SS, respectively.

As shown in Figure 6, when the aeration rate was increased, the decomposed carbon increased and reached a maximum value over 1.2 l min^{-1}. However, increasing the aeration rate was thought to be practically restricted because 1.2 l min^{-1} of aeration corresponded to 1200 h^{-1} of K_La, which was an oxygen supply condition maximally achievable in a large-scale common bioreactor (see *Oxygen Transfer* section). Therefore, studies on more efficient methods for oxygen supply deserve attention in order to develop and apply the full-scale slurry bioreactor system for the treatment of food wastes.

Interestingly, in the anoxic conditions (no aeration), the food wastes were not decomposed into gaseous CO_2 (Figure 6), while the considerable SS concentration decreased, as shown in Figure 5. Consequently, approximately 3.1 g carbon l^{-1} in SS was converted just into the dissolved form in the liquid phase.

Oxygen requirement

It is important to quantify the relationship between decomposed carbon and oxygen consumption. With a quasi-steady state assumption, the oxygen uptake rate (OUR(t)) is equal to the oxygen transfer rate (OTR(t)) [12]:

$$\mathrm{OUR}(t) \cong \mathrm{OTR}(t) = K_La[\mathrm{DO}^* - \mathrm{DO}(t)] \quad (g\,l^{-1}h^{-1})$$

where K_La is the volumetric oxygen transfer coefficient (h^{-1}), DO^* is the saturated concentration of DO (g l^{-1}), DO(t) is the DO concentration at an operation time, t (h). From Equation 3, the oxygen consumption (OC(t)), which is the cumulative amount of consumed oxygen, can be calculated by integrating OUR(t) for the total operating time (5 days):

$$\mathrm{OC}(t) = \int_0^t \mathrm{OUR}(t)dt = \int_0^t K_La[\mathrm{DO}^* - \mathrm{DO}(t)]dt \quad (g\,l^{-1})$$

The numerical integration in Equation 4 was carried out by a trapezoidal method [4] by using the technical computing software Mathematica 3.0 [14].

The decomposed carbon was almost linear with the oxygen consumption over the entire experimental range (Figure 7). This

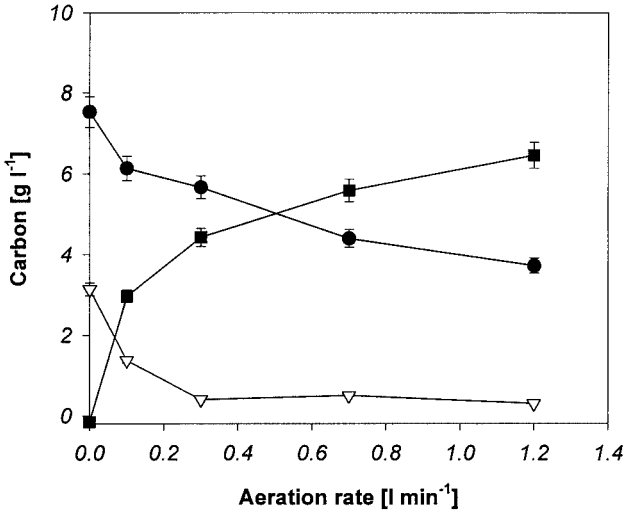

Figure 6 Migration of carbon after 5-day operation of the slurry bioreactor at various aeration rates. Error bars represent the standard deviations of three samples. ●, carbon in suspended solids; ▽, DOC; ■, decomposed carbon.

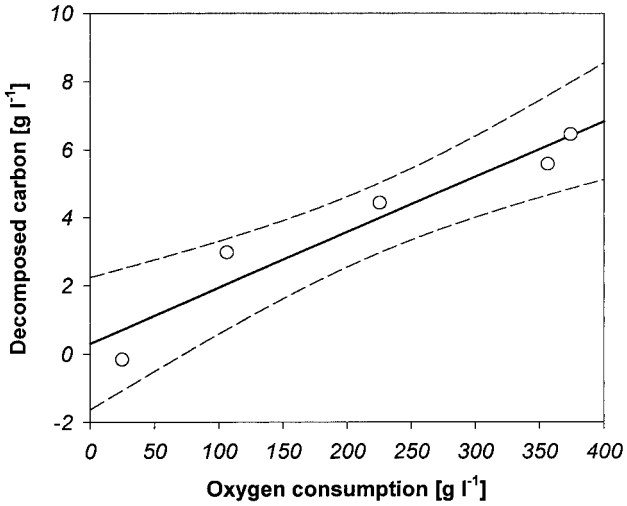

Figure 7 Relationship between decomposed carbon and oxygen consumption. The correlation coefficient of the solid line is 0.93 and the dashed line represents the interval of 95% confidence.

indicated that the decomposition of food wastes in the slurry bioreactor was limited by oxygen transfer and that oxygen transfer was the important operating parameter determining reactor performance. From the linear relationship, it was estimated that approximately 61.5 g oxygen was required for the removal of 1 g organic carbon from the bioreactor. Since the average carbon content of food wastes was 48.4%, the oxygen requirement on the basis of dried food wastes was as high as 29.8 g O_2 g^{-1} food wastes. The amount of organic carbon removed was estimated on the basis of the reduction of total organic carbon in the bioreactor (carbon in food wastes, microbial cells and dissolved organics). Since the oxygen requirement was evaluated by determining the amount of oxygen for the production of 1 g CO_2 (complete removal of 1 g organic carbon from the bioreactor), it was much higher than the theoretical value in ordinary fermentation. In addition, the value of K_La was probably overestimated since the K_La was determined in the bioreactor with pure water prior to the addition of food wastes, which could also contribute to the high value of the oxygen requirement. It is well known that high viscosity and ionic strength of the broth in the slurry bioreactor could significantly change the K_La value and the saturated oxygen concentration [9], which in turn affects the estimation of oxygen requirement.

Conclusions

The aeration rate significantly affected the decomposition of food wastes in a slurry bioreactor. As the aeration rate increased, the decomposition performance was enhanced, indicating that aeration rate was an important operating factor. In the anoxic condition, the organic carbon was not decomposed into inorganic carbon but just converted into DOC in the liquid phase. A linear relationship between the decomposed carbon and oxygen consumption was observed, from which the oxygen requirement was estimated to be 61.5 g O_2 g^{-1} carbon.

Acknowledgements

This work was financially supported, in part, by Dae-Nam Ind., Seoul, and the School of Environmental Engineering, Pohang University of Science and Technology, Pohang, South Korea.

References

1 Argelier S, JP Delgenes and R Moletta. 1998. Design of acidogenic reactors for the anaerobic treatment of the organic fraction of solid food waste. *Bioprocess Eng* 18: 309–315.
2 DeWilde B. 1997. Overview of EU composting infrastructure including policies, technology and current status. In: Proceedings of Symposium on Composting Waste Management System, Seoul, South Korea, pp. 59–68.
3 Finn RK. 1954. Agitation–aeration in the laboratory and in industry. *Bacteriol Rev* 18: 254–274.
4 Holland CD and Liapis AI. 1983. Computer Methods for Solving Dynamic Separation Problems. McGraw-Hill, New York.
5 Kim KE. 1997. Overview of Korean solid wastes management policies. In: Proceedings of Symposium on Composting Waste Management System, Seoul, South Korea, pp. 3–17.
6 Kim PJ, CW Chang and KH Min. 1995. Evaluation of the stability of compost made from food wastes by the fermenting tank. *J KOWREC* 3: 35–42.
7 Kubota H and K Nakasaki. 1991. Accelerated thermophilic composting of garbage. *Biocycle* 32: 66–68.
8 Matthur RS, AC Gaur, SP Magu and KV Sadasivam. 1986. Accelerated compost and improved yields. *Biocycle* 27: 42–42.
9 Riet K and J Tramper. 1991. Basic Bioreactor Design. Marcel Dekker, New York.
10 Shin PK. 1997. High-rate aerobic degradation of food wastes. In: Proceedings of Symposium on Composting Technology of Food and Organic Wastes, Seoul, South Korea, pp. 191–199.
11 Shin HS, EJ Hwang, YK Jeong, ST Kang and YJ Jeong. 1996. Study on operating conditions for high rate garbage composting. *J Korean Solid Wastes Eng Soc* 13: 202–210.
12 Shuler ML and F Kargi. 1992. Bioprocess Engineering; Basic Concepts. Prentice-Hall, Englewood Cliffs, NJ.
13 The Ministry of Environment of Korea. 1992. Strategies for Separate Collection and Proper Treatment of Organic Wastes. The Ministry of Environment of Korea, Seoul, South Korea.
14 Wolfram S. 1996. The Mathematica Book. Wolfram Research, Champaign, IL.
15 Yun HY, KY Yoo, HW Park, KS Kim and MJ Yu. 1994. Determination of optimum process variables in the design and operation of aerobic composting for food wastes. *J Korean Solid Wastes Eng Soc* 11: 377–387.
16 Yun Y-S, SB Lee, JM Park, C-I Lee and J-W Yang. 1997. Carbon dioxide fixation by algal cultivation using wastewater nutrients. *J Chem Technol Biotechnol* 69: 451–455.
17 Yun Y-S, JI Park, MS Suh and JM Park. 2000. Treatment of food wastes using slurry-phase decomposition. *Bioresource Technol* 73: 21–27.