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Optimum Operation of Thermophilic Aerobic Digestion Process for Waste Activated Sludge Minimization

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Abstract To achieve optimum operation of a thermophilic aerobic digestion (TAD) process for waste activated sludge (WAS), TAD experiments using *Bacillus stearothermophilus* (ATCC 31197) were carried out to investigate the optimum concentration of dissolved oxygen (DO). TAD reactors were operated at DO concentrations of 0, 1, 2, 3, 4, and 5 ppm, and the results showed that the WAS could be successfully degraded by a TAD system operated with a DO concentration of 1 ppm and above. When the TAD system with an optimum additive (2 mM Ca ion), selected from a previous study, and 1 ppm DO concentration were combined with a thermal pretreatment (121°C, 10 min), the results exhibited upgraded total suspended solids and an enhanced protein degradation.

Key words: Thermophilic aerobic digestion, waste activated sludge, dissolved oxygen, *Bacillus stearothermophilus*, optimization

The volume of waste activated sludge (WAS) currently produced from biological wastewater treatment processes has drastically increased as a result of the quantitative/qualitative expansion of wastewater treatment due to stringent environmental regulations. WAS is the main by-product of biological wastewater treatment processes and usually consists of 70% organic matter [6]. Stabilization is considered as one of the most attractive methods of reducing the organic fraction in WAS [12]. Thermophilic aerobic digestion (TAD) also has certain advantages compared with other conventional stabilization processes (e.g. mesophilic anaerobic digestion); *i.e.* pathogen inactivation, a short sludge residence time, sustainable ability for shock loads or toxic materials, and suitability for land application of treated WAS. As such, TAD processes have recently emerged as candidates for effective sludge disposal [7].

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To upgrade the performance of TAD processes, we previously investigated the effects of pretreatment on TAD performance [16, 17]. The pretreatments were found to rupture the cell wall and membranes of the bacteria in the WAS, thereby resulting in the release of cellular organic components. These organic substances, mainly proteins and carbohydrates, are then hydrolyzed into unit molecules by the extracellular enzymes excreted from thermophilic aerobic bacteria. However, during the digestion processes, it appeared that the hydrolysis of these proteins and carbohydrates was the rate-limiting step, which was insufficiently achieved by the exo-enzymes produced by the bacteria [10]. Therefore, thermostable proteases produced from thermophilic bacteria seem to be essential for the degradation of WAS in a TAD process. Indeed, several researchers reported that thermophilic aerobic bacterial culture supernatants were able to hydrolyze various soluble proteins [3, 8]. In addition, it has been known that metal ions play a role in the control of proteolytic activity [11, 18]. In a recent study by us [14], the proteases produced by *Bacillus stearothermophilus* (ATCC 31197), previously selected for the TAD process [15], were characterized and the enhancement of their activity was observed on the addition of several additives. Furthermore, TAD experiments with WAS were also conducted to investigate the effects of Ca^{2+}, Fe^{2+}, and Zn^{2+} on the digestion performance and to determine the optimum concentration of the selected additive.

The optimization of the operating parameters in a TAD process is important to obtain the best TAD performance. Indeed, the optimization of temperature and solid residence time enhances the TAD performance [5], and bacterial cells are decomposed into carboxylic acids and utilized under oxygen-limited conditions [9]. It is difficult to increase the level of the dissolved oxygen (DO) concentration in a TAD process due to low solubility of oxygen in water at a high temperature. Therefore, the DO concentration is an important operating factor for a cost effective TAD process due to the

high aeration cost involved. However, to the best of our knowledge, the optimization of the DO concentration for a TAD process has not yet been reported.

Accordingly, we investigated the effects of the DO concentration on TAD performance to find the optimum DO concentration for the cost effective operation of TAD processes. A TAD experiment with the optimum conditions was also conducted to compare with a control TAD. An optimized TAD experiment was carried out with selected additive [14] and DO concentration, using thermal pretreated WAS [16]. The additive condition and the thermal pretreatment method were obtained in our previous studies.

All chemicals were reagent grade, and the *B. stearothermophilus* (ATCC 31197) cell line purchased from ATCC was cultivated in a 250-ml flask with 100 ml of a medium (soluble starch 1 g, tryptone 0.5 g, yeast extract 0.5 g, $MnCl_2$ 0.05 g, KH_2PO_4 0.1 g, and $CaCl_2$ 0.05 g, pH 5) at 55°C with shaking at 200 rpm [1].

Industrial WAS was collected from the sludge thickener of a wastewater treatment process at an oil refinery plant in Korea. The characteristics of the raw sludge used are shown in Table 1. The TAD experiments were conducted using a 5-l bioreactor (Bio G-12, Hanil R&D Co., Seoul, Korea) with a working volume of 3 l at DO concentrations of 0, 1, 2, 3, 4, and 5 ppm to determine the optimum DO concentration for an effective TAD operation. The DO concentration was automatically maintained at the desired level by controlling the aeration rate and agitation speed, and air, humidified by passing it through water, was supplied into the bioreactor through a silicone tube membrane. Temperature (60°C), pH (between 7.0 and 8.0), and an impeller speed (300 rpm) were maintained throughout the experiments. The bioreactor was operated for more than 90 h.

The thermophilic bacteria, *B. stearothermophilus*, were collected from a flask culture during the late-exponential growth phase (15 h old). The bacteria were then concentrated by microfiltration using a cellulose ester membrane filter (MFS membrane filter, pore size 0.2 μm, ADVANTEC Inc, Pleasanton, CA, U.S.A.) and the concentrated bacteria were inoculated into the bioreactor with 3 l of prepared WAS. The inoculum concentration in batch experiments was 1.0 g wet cell weight/l.

A TAD experiment was also carried out with the proposed additive (2 mM calcium chloride [14]) and DO conditions, using pretreated WAS. Prior to conducting the TAD, the WAS was thermally pretreated with an autoclave (JISCO, Seoul, Korea) at 121°C and 1.5 atm pressure for 10 min [3]. The pretreated WAS was cooled to an ambient temperature before digestion.

Table 1. Characteristics of the WAS used for TAD experiments.

	TSS (g/l)	DOC (mg/l)	Extracellular protein (mg/l)
Initial concentration	17.2–24.0	179.5–375.1	7.2–37.0

The total suspended solid (TSS) concentration was measured using standard methods 2540D [2]. The samples were filtered through preweighted Whatman GF/C micro fibre filters, and then dried at 90°C for 24 h. The TSS concentration was calculated from the difference between them. The samples were centrifuged at 10,000 ×g, and the supernatants were analyzed for their DOC and extracellular protein concentrations. The dissolved organic carbon (DOC) concentration was assayed using a total organic carbon analyzer (TOC-5050A, Shimadzu Co., Tokyo, Japan). The protein concentrations were determined by the Bradford method using bovine serum albumin as the standard [4].

The performance of an aerobic microbial process depends essentially on the DO concentration, thus the operation costs of an aerobic process are largely affected by the aeration cost [13]. While oxygen excess conditions can result in the complete oxidation of biodegradable substrates, oxygen limited conditions can result in the formation of a significant concentration of soluble products with a low

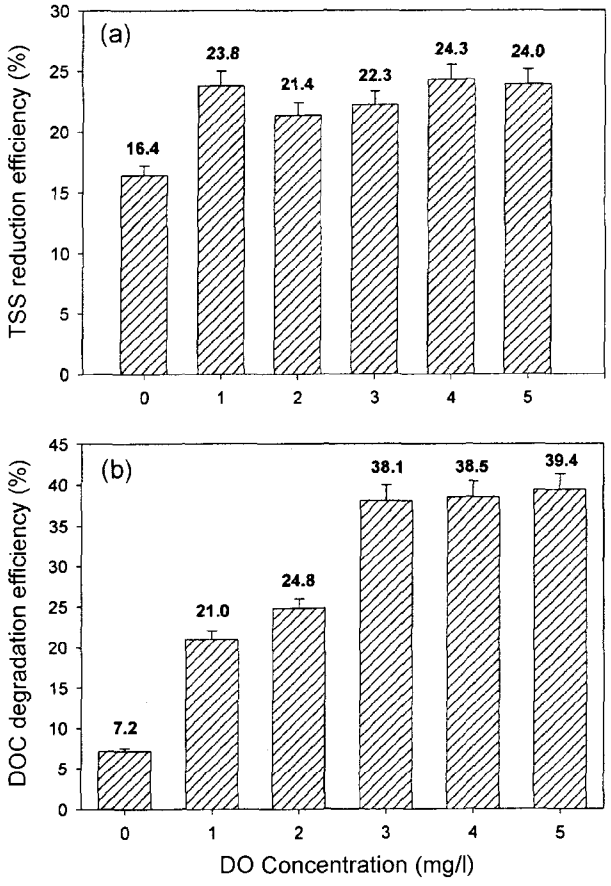

Fig. 1. Comparison of WAS degradation efficiencies according to DO concentration.
(a) TSS reduction, (b) DOC degradation.

biomass yield coefficient [19]. Therefore, the DO concentration of a TAD process must be determined to optimize the TAD performance and operation cost. The current TAD experiments were conducted using *B. stearothermophilus* within a DO range of 0-5 ppm, and the TAD performance was estimated in terms of the TSS reduction and DOC degradation (Fig. 1). The TSS reduction efficiency in the presence of DO concentration of 1 ppm and above exhibited higher values (21.4-24.3%) than that (16.4%) in the absence of oxygen. The TSS can be either increased by the growth of *B. stearothermophilus* or decreased by the lysis of activated sludge during the TAD experiment. The experimental result showed the reduction of TSS in TAD experiments, because the latter was predominant. It was also observed that active *B. stearothermophilus* in aerobic condition could improve the lysis of WAS. Although the experiment without aeration showed only a 7.2% DOC reduction, significant reductions of DOC (21.0–39.4% of the maximum DOC) was observed in the experiments with DO concentrations of 1 ppm and above. This result indicated that the released soluble components were successfully degraded due to the lysis of the WAS by the thermophilic bacteria in a DO concentration of 1 ppm and above. This could also be explained by the behavior of the pH in the time course (Fig. 2). In the experiment without aeration, the pH initially decreased sharply due to incomplete oxidation of the organic components into organic acids and stayed low, because there was no consumption of organic acids. However, the pH value rallied from the initial decrease in the experiments with DO concentrations of 1 ppm and above, because of the complete oxidation of the released organic components. The TSS reduction efficiency relative to the oxygen supply conditions (1 to 5 ppm) also exhibited similar values. Although the DOC reduction efficiency increased significantly up to 3 ppm DO concentration, the organic components released in the supernatant could be

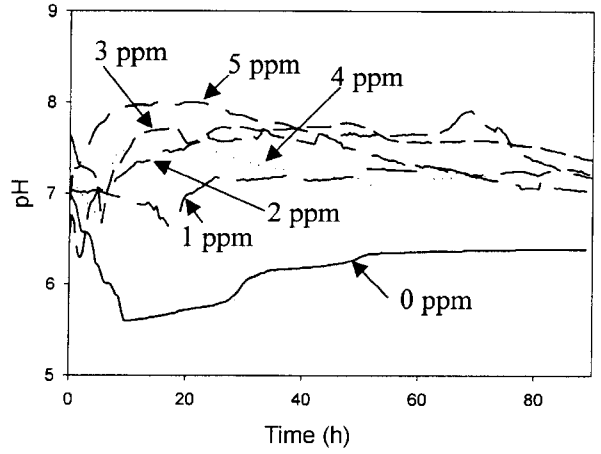

Fig. 2. Time course behavior of pH in TAD experiments with various DO concentrations.

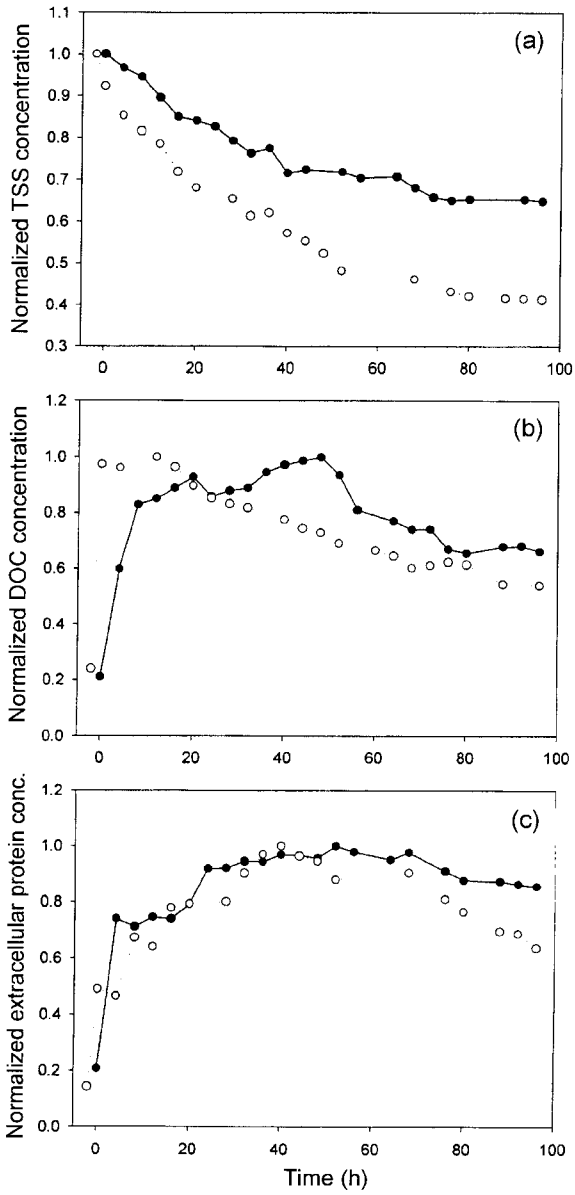

Fig. 3. Time course behavior of normalized (a) TSS, (b) DOC, and (c) extracellular protein concentration in control and proposed TAD experiments.
Symbols: ●, control TAD experiment; ○, optimal TAD experiment.

degraded by the wastewater treatment system by recycling the supernatant. Accordingly, based on TSS and DOC reductions and aeration cost saving, 1 ppm DO concentration was determined to be the optimum DO concentration for the TAD process.

The performance of the TAD experiment conducted with the optimum additive (2 mM calcium chloride), DO conditions (1 ppm), and thermally pretreated WAS was compared with that of a control TAD experiment (no pretreatment, no additives, and no DO control with excess aeration). In Fig. 3, the TSS reduction efficiency (58.6%)

was significantly higher than that (35.1%) of the control. It is likely that the thermal pretreatment produced this difference [16]. The TSS concentrations were normalized by an initial value for convenient comparison of reduction, while the DOC and extracellular protein concentrations were normalized by respective maximum values to compare the degradation by the thermophilic bacteria. As seen in Fig. 3, no sharp difference in the DOC reduction efficiency between the proposed TAD (46.0%) and control TAD (33.9%) experiments was observed. However, the extracellular protein reduction efficiency of the proposed TAD (36.4%) was drastically higher than that of the control TAD (14.6%), due to enhanced hydrolysis of the released protein by the Ca^{2+}-activated protease [14]. Thus, the results showed that the proposed TAD process exhibited significantly upgraded TSS and an enhanced protein degradation.

In conclusion, TAD experiments were conducted to determine the optimum DO concentration for a better TAD performance and lower aeration cost. From the results, it was concluded that a DO concentration of 1 ppm was effective for an economical TAD process operation. A TAD process with the optimum additive (2 mM calcium chloride) and DO concentration (1 ppm) was combined with a thermal pretreatment (121°C, 10 min). The proposed TAD system exhibited significantly enhanced performance in terms of the TSS and protein reduction efficiencies (58.6% and 36.4%, respectively), compared with those of the control experiment (35.1% and 14.6%, respectively).

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