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Aeration Control of Thermophilic Aerobic Digestion Using Fluorescence Monitoring

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The thermophilic aerobic digestion (TAD) process is recognized as an effective method for rapid waste activated sludge (WAS) degradation and the deactivation of pathogenic microorganisms. Yet, high energy costs due to heating and aeration have limited the commercialization of economical TAD processes. Previous research on autothermal thermophilic aerobic digestion (ATAD) has already reduced the heating cost. However, only a few studies have focused on reducing the aeration cost. Therefore, this study applied a two-step aeration control strategy to a fill-and-draw mode semicontinuous TAD process. The NADH-dependent fluorescence was monitored throughout the TAD experiment, and the aeration rate shifted according to the fluorescence intensity. As a result, the simple two-step aeration control operation achieved a 20.3% reduction in the total aeration, while maintaining an effective and stable operation. It is also expected that more savings can be achieved with a further reduction of the lower aeration rate or multisegmentation of the aeration rate.

Keywords: Waste activated sludge, thermophilic aerobic digestion, fluorescence, aeration control, stabilization

The activated sludge process is the most widely used biological wastewater treatment process, and its major by-product is waste activated sludge (WAS), which mainly consists of a microbial biomass. However, as a result of the quantitative expansion of the production of WAS, treatment techniques for the reduction and recycling of WAS have become spotlighted. Biological stabilization is considered one of the most attractive methods of reducing WAS, as WAS usually consists of more than 70% organic matter [5]. To minimize WAS, mesophilic anaerobic digestion processes are commonly used as a conventional biostabilization technique [21]. Yet, despite the production of a useful gas (CH_4), these processes have various disadvantages, including the incomplete inactivation of pathogenic microbes and a low WAS degradation rate, due to the extremely slow growth of methanogenic bacteria [10]. Therefore, thermophilic digestion processes, whether aerobic or anaerobic, have emerged as effective alternatives. Although thermophilic anaerobic digestion includes CH_4 production and pathogen pasteurization, its reaction rate is too slow, resulting in a lengthy treatment process. Therefore, thermophilic aerobic digestion (TAD) has been highlighted because of its more rapid sludge degradation rate and ability to sterilize pathogenic organisms [14, 22]. Thus, in spite of the disadvantage of no CH_4 production, TAD is considered as the most promising candidate for small-size units and effective WAS stabilization (especially for small municipal sewage water and industrial wastewater treatment plants). Several studies of TAD have already made significant improvements as regards biomass and pathogen reduction [2, 3, 9, 12, 25, 28]. Moreover, the current authors have investigated TAD processes to enhance their performance and optimize the operation parameters [13–18].

When compared with mesophilic anaerobic digestion systems, the operating costs of a TAD system are high, due to the energy required to maintain a high temperature and for aeration to sustain aerobic conditions, thereby limiting the commercialization of TAD processes. Consequently, several studies have explored the inclusion of an autothermal process using heat produced from an exothermal aerobic biological reaction to deal with the need for a high temperature [8, 9, 23], and this autothermal process, generally called autothermal thermophilic aerobic digestion (ATAD), has already been installed in more than 40 plants in several countries including Canada, Germany, Switzerland, and the U.S.A. [3, 12]. Meanwhile, only a few studies

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have attempted to optimize the dissolved oxygen (DO) concentration [4, 10, 17, 29], where the focus was on controlling the DO concentration to minimize the volatile fatty acid accumulation. Accordingly, this study investigated reducing the operating costs by controlling the aeration rate.

Controlling the aeration rate for a stable TAD operation requires a reliable process monitoring technique (especially for the physiological state of living cells). Information on the cellular reactions and bioenergetics in a biological system is essential to optimize and control a biological process [24, 27]. Thus, various parameters, including the pH, DO concentration, and oxidation-reduction potential (ORP), have already been investigated for controlling a digestion system [1, 6, 29]. However, measuring the optical fluorescence would seem to have specific advantages, including long-term stability, no requirement for frequent calibration and maintenance, a good response time, accuracy, and sensitivity [14, 19], whereas pH, DO, and ORP measurements are not suitable for long-term continuous monitoring, plus the pH and ORP are inappropriate as control parameters owing to their extremely high nonlinearity. In addition, they describe the conditions of water phase, not that of sludge. Therefore, online monitoring of the optical fluorescence is more suitable to understand the biological status in a complex digestion system and to control a TAD system.

Although many biological compounds, such as proteins, enzymes, coenzymes, and metabolites, emit a unique fluorescence after light excitation [20], reduced nicotinamide adenine dinucleotide (NADH) and reduced nicotinamide adenine dinucleotide phosphate (NADPH) are the most important compounds with a fluorescent property, as they are present in all living cells and play an important role in the microbial metabolism. Thus, the cellular NADH (or NADPH) level is a non-invasive indicator of the cellular status and can conveniently be measured through fluorescence [11, 26].

Therefore, in this study, the NADH-dependent fluorescence (emission wavelength of 460 nm) was measured after the radiation of excitation light at 340 nm. As such, the online monitored fluorescence intensity depends on the physiological activity of the living thermophilic microorganisms in the TAD system, rather than the dead mesophilic microorganisms (main component of WAS). In a previous study by the current authors, stable control of a TAD operation was achieved using a food (WAS) replacement [18]. Therefore, this study combined food replacement and aeration rate control based on measuring the fluorescence value to maintain an economical and stable operation of a TAD system. A fuzzy logic controller, as mentioned in our previous paper [18], was applied to control the WAS replacement interval in a semicontinuous (fill-and-draw) digestion process.

Materials and Methods

Materials

Bacillus stearothermophilus (ATCC 31197) was cultivated in a 250-ml flask with 100 ml of a medium containing 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 5.0 at 60°C with shaking at 200 rpm in a shaking incubator (VS-8480S, Vision Scientific Co., Seoul, Korea). All the chemicals were purchased as reagent grade.

The WAS used for the experiments was collected from the sludge thickener of a wastewater treatment plant at a factory farm in Chonan, Korea. After sampling, the WAS was shipped immediately in an iced container and then stored at 4°C in a refrigerator. The sampled WAS was used in the experiments within 48 h to minimize any change in the sludge properties. The total suspended solids (TSS) concentration was within a range of 9–15 g/l.

Experimental Setup

All the digestion experiments were conducted at room temperature, and the configuration of the sensor system is described in our previous paper [18]. As the process liquid containing NADH emits light energy in the visible spectrum (wavelength 460 nm) from excited light (wavelength 340 nm), the fluorescence light was detected and transferred into an electric voltage signal using a biased photodetector (Model 818-BB-40, Newport Corp., CA, U.S.A.). The whole experimental setup, including the optical sensor and bioreactor system, was placed in a chamber made with opaque black acrylic resin to block any undesired light. In our previous study [18], performance tests with the sensor system were conducted using a pure β-NADH solution within a range of 1.0 to 250 μM and the *B. stearothermophilus* culture broth.

Batch and Semicontinuous TAD Experiments Without Aeration Control

The TAD experiments were performed in a 5-l laboratory scale bioreactor (KF-SL, KoBioTech Inc., Inchon, Korea) with a working volume of 2.5 l in batch and semicontinuous (fill-and-draw) operation modes. A temperature of 60°C and impeller speed of 250 rpm were maintained throughout the experiments. Air, humidified by bubbling it through water, was supplied to the bioreactor at a flow rate of 1.0 vvm (air vol/liquid vol-min) to maintain aerobic conditions. The temperature, pH, DO concentration, and impeller speed were all automatically monitored using a bioreactor monitoring system, and their average values recorded every 2 h. The inoculum concentration of *B. stearothermophilus* was 3.0 g wet cell weight/2.5 l solution. The bioreactor was operated for up to 96 h in a batch mode and 192 h in a semicontinuous mode. In the semicontinuous mode, the digester was operated based on a fill-and-draw cycle with a 40 vol% replacement. During the 192 h of operation, a cycle time of 48 h was applied, as used for the batch mode experiments in our previous study. In the batch experiments, samples were collected every 4 h to monitor the total suspended solids (TSS), total chemical oxygen demand (TCOD), and soluble chemical oxygen demand (SCOD). The TSS was analyzed every 6 h during the semicontinuous mode. In addition, the evaporative loss was estimated by measuring the WAS volume daily, and sterilized deionized water added to compensate for any volume loss. The NADH-dependent fluorescence was measured continuously using a home-made sensor system, and the intensity recorded as an average value every 2 h.

Aeration-Controlled Semicontinuous TAD Experiment

Fluorescence signal-dependent control of the aeration rate was applied to operate the semicontinuous TAD based on two aeration rates: 1.0 vvm for an active biological state and 0.5 vvm for a non-active biological state. The aeration rate was shifted based on an analysis of the fluorescence sensor signal. When the sensor signal decreased sharply, the aeration rate was shifted from 1.0 vvm to 0.5 vvm. However, in the case of a sharp decrease in the sensor signal when replacing the WAS, the aeration rate was returned to 1.0 vvm, as this signal decrease was likely caused by the loss of active thermophiles due to the withdrawal of the digested solution. The WAS replacement time was determined by the simple fuzzy logic controller using the fluorescence sensor signal, as described in our previous paper [18].

Analytic Method

The TSS concentration was measured using the Standard Method 2540D and was expressed as g/l. WAS samples of 10 ml were filtered through a preweighed glass microfiber filter (GF/C, pore size 1.2 mm; Whatman Ltd, Maidstone, U.K.), and then the filter cakes were dried at 80°C for 24 h, reweighed, and the difference was used to calculate the TSS concentration. Meanwhile, the TCOD and SCOD were measured by a spectrophotometric method using an HACH spectrophotometer (DR 2500; HACH Co., Loveland, CO, U.S.A.).

RESULTS AND DISCUSSION

Batch and Semicontinuous TAD Operations Without Aeration Control

To characterize the TAD system and verify the effectiveness of the sensor system to measure the physiological state of the TAD process, batch TAD experiments were conducted using a bioreactor and the results are shown in Figs. 1A–1C. Batch experiments for 96 h generated a fluorescence profile of the digestion process and its correlation with important process parameters, such as the TSS (or TCOD) reduction and DO changes. The profiles of the fluorescence sensor signal, TSS reduction, TCOD and SCOD, and DO changes are shown in Figs. 1A, 1B, and 1C, respectively.

In Fig. 1A, the fluorescence increased rapidly during the initial stage (until about 6 h) and remained at a high level until 24 h. During this period, the thermophiles were likely in the growth phase and stationary phase, respectively. Thus, the initial rise in the fluorescence corresponded to fast sludge degradation, as shown in Fig. 1A. The fluorescence then decreased for a period of 24 to 32 h, corresponding to the death phase for the thermophiles. This rapid decline in the fluorescence was then followed by a slight increase for a period of 32 to 42 h, which likely corresponded to autodigestion in the substrate starvation environment [7]. Thereafter, the fluorescence decreased continuously until the end of the batch process. This predicted growth pattern of the thermophiles also matched the TSS and TCOD reduction profiles (Figs. 1A and 1B), and also explained the time course behavior of the SCOD

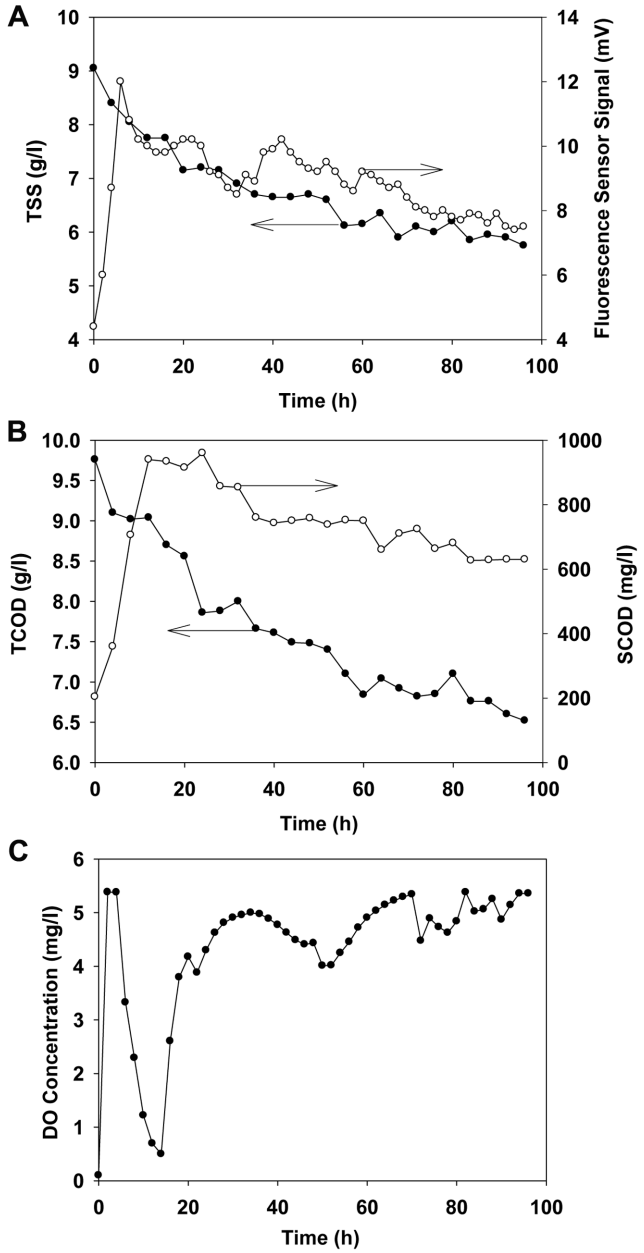

Fig. 1. Profiles of (**A**) TSS and fluorescence (●: TSS; ○: fluorescence sensor signal), (**B**) TCOD and SCOD (●: TCOD; ○: SCOD), and (**C**) DO concentration in a batch thermophilic aerobic digestion system.

and DO (Figs. 1B and 1C). The final reduction efficiency of the TSS in the batch operation was 36.4%. Therefore, from the results of the batch experiment, it was concluded that the sludge degradation was essentially completed within 32 h, which was then followed by the autodigestion of *B. stearothermophilus*. Therefore, a turnover time of 2 days was selected to achieve effective TSS reduction and maintain the activity of the thermophiles for a semicontinuous operation. The change of the DO in the batch TAD process

is shown in Fig. 1C. After an initial rapid increase, coinciding with the start of the aeration, a rapid decrease was observed from 4 to 14 h, after which the DO increased. The explanation for this is that the thermophiles were in the growth phase until 14 h, after which the DO values increased sharply, and then remained stable, except for the autodigestion period.

In the semicontinuous operation, the digester was operated based on a fill-and-draw cycle with a 40 vol% replacement. A cycle time of 48 h was employed for the semicontinuous operation of 192 h, and the recycling time was based on the results of the batch digestion experiment. The fluorescence profile and its correlation with the TSS reduction were monitored throughout the experiment, as shown in Fig. 2A. The DO profile is also shown in Fig. 2B.

In Fig. 2A, the TSS concentration continued to decrease during the first two cycles, as the first cycle did not achieve full TSS reduction according to the TAD capacity. Meanwhile, the third and fourth cycles exhibited a pseudo-steady state, as the lower TSS values for these cycles were similar to the TSS value for the second cycle. Thus, from the results of the semicontinuous operation, the TSS reduction efficiency was regarded as approximately 42.6%. This reduction efficiency was slightly higher than that from the batch experiment (36.5%), which was possibly due to a difference in the initial TSS concentrations, 9.05 g/l for the batch operation and 14.8 g/l for the semicontinuous operation. Thus, since the high particulate concentration was more readily degraded than the low particulate concentration, this indicated a higher degradation efficiency. However, even though the lower TSS concentration from the second cycle to the fourth cycle showed a similar value, the fluorescence profile showed an unstable (unsteady state) operation. In the third cycle, there was no initial sharp increase in the fluorescence, and the fluorescence peak for the fourth cycle was not as high as those for the previous cycles. Therefore, this indicated a break in the biologically stable operation in the continuous mode due to a lack of control. It was also confirmed by the unstable profile for the DO in the third and fourth cycles, as shown in Fig. 2B.

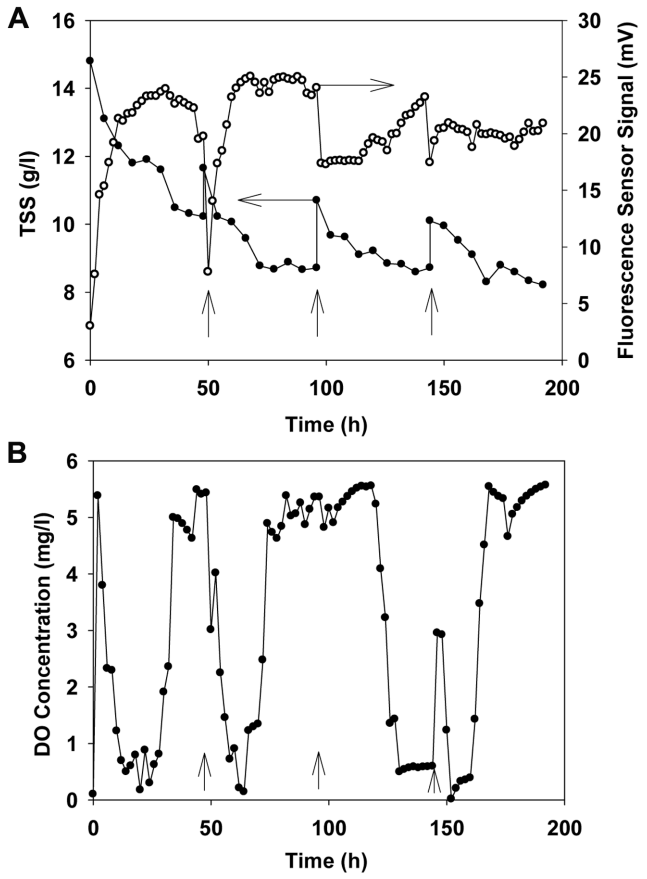

Fig. 2. Profiles of measured values in a semicontinuous (fill-and-draw cycle) TAD process without aeration control: **A**. TSS and fluorescence (●: TSS; ○: fluorescence sensor signal). **B**. DO concentration (vertical arrows: feeding point of fresh WAS).

Fluorescence-Dependent Aeration Control in Semi-continuous TAD

The results of the uncontrolled semicontinuous TAD operation clearly indicated the need for process control to maintain a steady-state (stable) operation of the TAD process. It was also confirmed that NADH-dependent fluorescence is an excellent indicator for the digestion process status. In our previous paper [18], fluorescence-dependent control of the WAS replacement time was shown to be efficient for the stable operation of semicontinuous TAD. Thus, the previously developed WAS replacement strategy was also applied to the proposed aeration-controlled semicontinuous TAD system.

The aim of this study is the development of an aeration control strategy for economical semicontinuous TAD processes. In TAD processes, the oxygen concentration is often a limiting factor, due to the high oxygen demand with the rapid growth of the thermophiles and low solubility of oxygen at high temperatures. It has also been reported that oxygen limitation (low DO concentration) results in the accumulation of volatile fatty acids (VFAs) and a low degradation efficiency of waste solids [29]. Therefore, commercialized TAD processes are commonly operated using a high aeration rate to prevent oxygen limited conditions. However, a high aeration rate results in high aeration costs and evaporative cooling during the ATAD (self-heating process). Yet, a high aeration rate is only really needed during the initial rapid growth phase, and otherwise induces a high DO concentration. Thus, to achieve an economical TAD process, the aeration rate should be controlled. In this study, a high aeration rate was applied to prevent oxygen starvation conditions during the

active growth period for the thermophiles, and a low aeration rate was applied during the non-active period for the thermophiles.

As a result, an economical TAD process can be achieved without reducing the process efficiency, as the aeration rate is only decreased when the process does not require much oxygen. In the semicontinuous TAD experiments with a fill-and-draw mode, a high aeration rate (1.0 vvm) was supplied during the initial period of every new cycle, and a relatively low aeration rate (0.5 vvm) maintained during the non-active period for the thermophiles. The shift time was determined based on a significant decrease in the fluorescence signal. Other studies [29] have reported that aeration rates of 1.0 vvm and 0.5 vvm are adequate to operate an effective TAD process without performance reduction. The results of the two-step aeration control are shown in Figs. 3A and 3B. The basic conditions, except for the aeration control, were same as those in the semicontinuous TAD experiments. The WAS replacement control in the fill-and-draw operation was conducted using a fuzzy logic controller, as described in our previous paper [18]. Two inputs to the fuzzy controller were used for the decision making: the error between the measured fluorescence signal and the set-point for the fluorescence signal, and changes in the error. According to if-then rules using expert knowledge, when the fluorescence signal decreased significantly (error was negative and large) and the change in the error was zero or a positive value, 40% of the treated WAS was replaced with the same volume of fresh WAS. In the experiment, the WAS was replaced six times during the 192 h of operation.

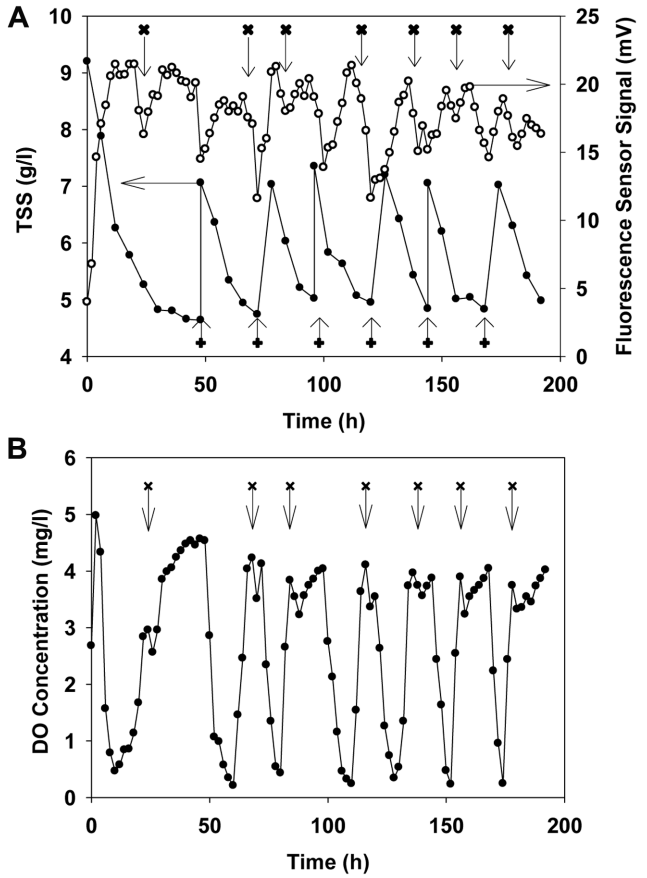

Fig. 3. Profiles of operation parameters in a two-step aeration-controlled semicontinuous (fill-and-draw) TAD process: **A**. TSS and fluorescence (●: TSS; ○: fluorescence sensor signal). **B**. DO concentration (cross symbols and vertical arrows: feeding point of fresh WAS; x symbols and vertical arrows: shift down point of aeration).

The shift from a high aeration rate to a low aeration rate was decided by analyzing the fluorescence signal. If the measured fluorescence signal dropped over the standard deviation and noise range, the aeration rate was shifted to the low value, as a significant decrease in the sensor signal was assumed to indicate the end of the growth phase for the thermophiles. After the WAS had been replaced with fresh WAS, a high aeration rate was applied, as it was expected that the addition of the fresh substrate (WAS) would activate the growth of the thermophiles. The aeration rate was shifted to the lower rate 7 times during the experiment, where the high aeration rate was used for 114 h, while the low aeration rate was used for 78 h. Thus, when compared with the TAD experiment with uncontrolled aeration, where the aeration rate was maintained at 1.0 vvm during the whole experiment, the aeration control reduced the total aeration by 20.3%. Although the aeration reduction is not proportionally related to the reduction in aeration costs, a considerable saving can still be achieved. Further savings on the aeration cost could also be achieved by decreasing the low aeration rate or through multistep control of the aeration rate.

Therefore, the results of semicontinuous TAD experiment with aeration control verified that WAS replacement and aeration control based on measuring the fluorescence signal can create a stable and economical operation (Fig. 3A). As shown in Fig. 3B, the DO concentrations were approx. 4 ppm during the non-active growth periods for the thermophilic microbes. According to our previous work [18], WAS degradation can be maintained at a DO concentration of 1 ppm and above. Therefore, lowering the aeration rate further or a detailed segmentation of the aeration rate could make the TAD process even more economical.

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