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Determination of optimal operating factors via modeling for livestock wastewater treatment: Comparison of simulated and experimental data

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ABSTRACT

This study evaluated the optimized operational conditions of a modified four-stage Bardenpho process via modeling for livestock wastewater treatment. The objective is to determine whether the effluent Korean water quality standards can be met using the modified process and ozone/activated carbon reactors. The parameters related to microbial respiration (i.e., Y_H, Y_A, μ_H, b_H, and i_{XB}) and effluent concentrations (i.e., f_p, η_g, K_h, and η_h) in GPS-X based on ASM1 were calibrated according to the influent characteristics. Consequently, the differences in the COD and TN concentrations of the calibrated and experimental results were 29.58 and 19.15 mg/L, respectively. A modeling method based on multiple RSM was used to determine the optimized operational conditions, resulting in a DO concentration of 6.6 mg/L in each aerobic reactor, an internal recycling rate of $4.9Q_{in}$, and a sludge recycling rate of $1.4Q_{in}$. Although the COD and TN concentrations during actual operation using the optimized conditions were slightly different than those predicted by GPS-X, the differences were not significant; therefore, the effluent Korean water quality standards were satisfied. With more specific criteria that reduce the differences between the predicted and actual concentrations, the modeling method for operational optimization would be sufficient under any circumstances.

1. Introduction

Recently, livestock head counts have been increasing rapidly because the consumption of livestock products has been growing along with the continuous economic growth. Ocean dumping of waste and wastewater has been prohibited since 2012 following revisions to the Prevention of Marine Pollution Act enforcement regulations. As a result, vast amounts of livestock waste and wastewater are being generated in Korea. The environmental pollution load caused by livestock wastewater is particularly large because of the high concentrations of organic matter, nitrogen, and phosphate; thus, it is difficult to meet Korean effluent water quality standards using conventional wastewater treatment processes (Ferreira et al., 2003; Juteau et al., 2004; Lee and Shoda, 2008). In case livestock wastewater, which is not treated under effluent water quality standards, is discharged into streams, it may cause eutrophication, toxic effects, and disease (Ji et al., 2011). Thus, studies of advanced and optimized treatment processes for livestock wastewater are necessary.

There are several approaches to developing advanced treatment processes and determining optimal operating conditions. One of them is the empirical approach, in which the effects of several operating factors can be generally tested through laboratory or pilot-scale operations. This approach has been proven to be highly inefficient in terms of both time and money (Hu et al., 2012). A model-based approach is an alternative way to solve the aforementioned problems; specifically, activated sludge models (ASMs), which were developed by a task group of the International Water Association (IWA) (Balku, 2007; Rivas et al., 2008), are the most widely used.

To be able to use ASMs, however, it is necessary to calibrate their default parameters. As most ASMs use default values of parameters for European wastewater characteristics, such as wastewater properties, environmental factors, and species of active microorganisms, they do not enable precise predictions (Abusam et al., 2001; Sin et al., 2005; Ruano et al., 2007). Hence, studies on the

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calibration of ASM parameter values have been performed using representative calibration methods including BIOMATH, STOWA, HSG, WERF, and EMSEL (Kim et al., 2010; Corominas et al., 2011; Lim et al., 2012). Most of the studies have used typical wastewater characteristics, while a few studies have analyzed wastewater with high concentrations of contaminants, such as livestock, food processing, and textile wastewater.

The application of ASMs to advanced wastewater treatment processes has become more difficult due to the recognition of new phenomena and the introduction of new variables and parameter values, which must be expressed in the models (Liwarska-Bizukojc et al., 2011). Many research efforts have been conducted to solve these problems and some notable solutions have been reported. Jiang et al. (2005) concluded that kinetic parameters and influent characterizations were most important when ASMs were applied to advanced treatment processes. Delrue et al. (2010) discussed that application of ASMs to a full-scale membrane bioreactor could be reasonably done by performing an influent characterization and calibration of the aeration parameters. These previous studies have made it clear that it is necessary to calibrate ASM parameters and apply modeling results to a pilot- or full-scale plant in order to accurately describe the overall behavior of advanced wastewater treatment processes.

The existing advanced treatment process is comprised of a modified four-stage Bardenpho process; this method was employed for livestock wastewater treatment in this study. The objective of the present study was to find the optimized operational conditions via modeling of a modified four-stage Bardenpho process in order to meet the Korean effluent water quality standards. As mentioned above, calibration and evaluation of parameters were necessary for livestock wastewater treatment using this advanced wastewater treatment process due to the lack of an appropriate prediction from a model-based approach. The ASM parameters were thus calibrated to fit the characteristics of domestic livestock wastewater and advanced treatment processes such as a membrane bioreactor and a high-efficiency air-transferring device were applied. This paper also describes an investigation of removal efficiency improvements for organic matter and nitrogen identified by operating a pilot-scale plant and optimizing the operational results. Based on the results obtained from the pilot-scale plant's operation, revisions to the model-based approach to precise predictions were suggested.

2. Materials and methods

2.1. Advanced wastewater treatment process

The present study was conducted on livestock wastewater generated from a farm located in Gunsan, Korea that raises 2000 cattle. The average raw-water flow rate was 8 m^3/d and the influent concentrations of COD, TN, and TP along with the effluent Korean water quality standards are shown in Table 1. The newly suggested process (termed 'existing advanced process' throughout this paper) for livestock wastewater treatment is a modified four-stage Bardenpho process with ozone/activated carbon reactors. A schematic diagram of the existing advanced process is shown in Fig. 1. The removal efficiencies of the ozone/activated carbon reactors were constant at about 80% for COD and 15% for TN in the preliminary experiments. Therefore, the effluent concentrations of the modified four-stage Bardenpho process required to meet the effluent Korean water quality standards are set at 750 mg COD/L and 60 mg TN/L.

The modified four-stage Bardenpho process is an advanced biological treatment process involving a 1st anoxic reactor, Bio Jet Reactor™ (BJR), 2nd anoxic reactor, and membrane bioreactor (MBR). For the highly efficient removal of organic matter and nitrogen, a BJR with a high-efficiency air-transferring device and an MF membrane module (Mitsubishi Co., Japan) were installed as the 1st and 2nd aerobic reactors, respectively.

Table 1
Concentrations of influent raw water and effluent Korean water quality standards.

Constituent	Average influent concentration (mg/L)		Effluent Korean water quality standard (mg/L)
	Existing advanced process	Modified four-stage Bardenpho process	
COD_{Mn}	22,023	5536	≤50
COD_{Cr}	70,474	17,524	[a]
TN	5790	3108	≤60
$NO_3^- - N$	60	23	–
$NH_4^+ - N$	4356	2537	–
TP	1267	74	≤8
$PO_4^{3-} - P$	1103	61	–

[a] South Korea does not have existing water quality standards for COD_{Cr}. As the influent ratio of COD_{Cr}/COD_{Mn} is 3:1, the target for COD_{Cr} is set at 150 mg/L in this study. COD_{Cr} is referred to as 'COD' throughout this paper.

2.2. Parameter calibration and operational optimization

The GPS-X 6.1.1 (Hydromantis, Canada) simulation program was used for parameter calibration and operating-factor optimization, and the simulated layout of the modified four-stage Bardenpho process obtained via GPS-X is shown in Fig. 2. The CN library of ASM1 was employed to predict the effluent concentrations of COD and TN, which are the targets for minimization in this study.

As shown in Table 2, ASM1 is composed of 19 stoichiometric and dynamic parameters, which were calibrated via the Environmental Management and Systems Engineering Lab (EMSEL) protocol suggested by Kim et al. (2009). The EMSEL protocol, which consisted of an integrated scheme for modeling, sensitivity analysis, design of experiments, and response surface methodology (RSM), was suitable for performing optimization of the process for more than one response variable (Lim et al., 2011). The EMSEL protocol uses the ASM calibration method, which selects parameters to minimize the difference between the predicted and experimental concentrations including influent characteristics, sensitivity analysis, and RSM. The operational optimization factors were determined via sensitivity analysis and RSM based on the calibrated parameters of GPS-X. The RSM was performed for the experimental design, design analysis, and optimization. The overall flowchart for parameter calibration and operating-factor optimization is shown in Fig. 3.

2.2.1. Influent characteristics

Input parameters, such as the COD fractions (i.e., S_I, S_S, X_I, and X_S) and TN fractions (i.e., S_{NH}, S_{NO}, S_{ND}, and X_{ND}) of the influent, were required to accurately predict the effluent concentrations using GPS-X. The influent characteristics were analyzed to determine the input parameters via oxygen uptake rate tests on the batch scale (Avcioğlu et al., 2003; Wu et al., 2009). For parameter calibration, the influent characteristics were used to estimate parameter values related to microbial respiration, such as Y_H, Y_A, μ_H, b_H, and i_{XB}, using the estimation equations suggested by Petersen et al. (2002). The suggested estimation equations are shown in Table 3.

2.2.2. Sensitivity analysis

Sensitivity analysis was performed mainly to determine the sensitive parameters for parameter calibration and optimal operating factors for operation-factor optimization that influence the COD and TN concentrations of the effluent. The analysis method used is a one-way sensitivity analysis that involves sequentially varying each parameter while keeping the others constant. The parameters ranged from 50 to 150% with default values of 100%, and the sensitivity was analyzed in intervals of 10%.