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Treatment of swine wastewater in continuous activated sludge systems under different dissolved oxygen conditions: Reactor operation and evaluation using modelling

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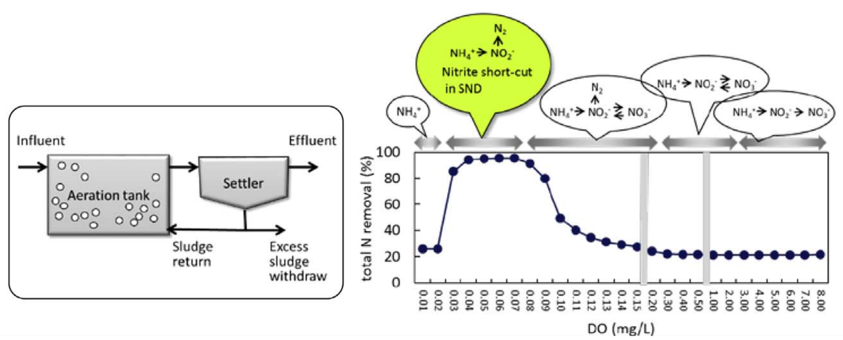
GRAPHICAL ABSTRACT



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ABSTRACT

Swine wastewater was treated in two continuously aerated activated sludge (AS) systems at high (AS1: 1.7–2.6 mg/L) and low (AS2: 0.04–0.08 mg/L) dissolved oxygen (DO), and at three temperatures (10, 20, and 30 °C). Biochemical oxygen demand (BOD) removal was > 94.8%. Meanwhile, total nitrogen (N) removal was significantly higher in AS2, at 64, 89, and 88%, than in AS1, at 12, 24, and 46%, for 10, 20, and 30 °C, respectively. The experimental data were considered in a simulation study using an AS model for BOD and N removal, which also included nitrite, free ammonia, free nitrous acid, and temperature. Simulations at high-DO showed that ammonium was partly oxidized into nitrate but not removed, whereas at low-DO ammonium was removed mainly through the nitrite shortcut in simultaneous nitrification–denitrification. This study demonstrates that treatment at low-DO is an effective method for removing N, and modelling a helpful tool for its optimization.

Abbreviations: anammox (AMX), anaerobic ammonium oxidation; AOB, ammonium-oxidizing bacteria; AS, activated sludge; ASM, AS model; BOD_5, 5-d biochemical oxygen demand; COD, chemical oxygen demand; CSTR, continuous stirred-tank reactor; DO, dissolved oxygen; EUB, eubacteria; FA, free ammonia (NH_3); FNA, free nitrous acid (HNO_2); N, nitrogen; N_2, nitrogen gas; N_2O, nitrous oxide; NH_4^+, total ammonium; NO_2^-, total nitrite; NO_3^-, nitrate; NOB, nitrite-oxidizing bacteria; PO_4, total phosphate; q-PCR, quantitative polymerase chain reaction; SBR, sequencing batch reactor; SND, simultaneous nitrification and denitrification; t-C, total carbon; t-IC, total inorganic carbon; t-IN, total inorganic N; t-OC, total organic carbon; t-ON, total organic N; t-N, total N; TSS, total suspended solids; VSS, volatile suspended solids

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1. Introduction

Livestock production contributes substantially to the economy of Japan, representing about 35% of the agricultural gross production. The amount of organic waste generated by this productive sector is equivalent to 20% of the total amount of industrial waste generated in the country. Hence, the livestock sector is potentially responsible for several issues that can affect the environment. Livestock waste is indeed one of the major causes of nitrogen (N) pollution in public water bodies (Steinfeld et al., 2006) and pollutant gaseous emissions worldwide such as ammonia (NH_3) and greenhouse gases including nitrous oxide (N_2O; Gac et al., 2007). In Japanese pig farms, such wastes are often separated into solid and liquid fractions. Commonly used subsequently processing includes composting for the solid fraction and aerobic treatment in an activated sludge (AS) system for the liquid fraction, hereafter referred to as swine wastewater. According to government sources, 61% of such swine wastewater is aerobically treated. The most popular discharge standard for Japanese livestock farms in 2017 was 600 mg N/L (NO_2^--N + NO_3^--N + 0.4·NH_4^+-N). However, this value is expected to be reduced soon to meet the discharge standard currently applied to other activities, and which is fixed at 100 mg N/L.

The organic content in swine wastewater, in terms of five-day biochemical oxygen demand (BOD_5) and total nitrogen (t-N), are high and variable among farms and seasons. The average values and standard deviation for raw swine manure before solid–liquid separation, as reported by Waki et al. (2010a), are 8700 ± 5200 mg BOD_5/L and 2500 ± 1300 mg t-N/L with ranges of 2000–22000 and 58–5500, respectively. The AS systems implemented in pig farms are quite heterogeneous; a significant part of them aim to remove BOD_5 but not N. According to the aforementioned authors (Waki et al., 2010a), average values in the treated effluents are 59 ± 83 mg BOD_5/L and 430 ± 540 mg t-N/L. Thus, the improvement of these treatment plants by including N-removal is urgent in order to reduce environmental impacts linked to pig farming.

Conventionally, biological N-removal from swine wastewater is achieved by combining autotrophic nitrification under aerobic conditions and heterotrophic denitrification under anoxic conditions. Nitrification consists of sequential oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) by ammonium-oxidizing bacteria (AOB), and nitrite to nitrate (NO_3^-) by nitrite-oxidizing bacteria (NOB). On the contrary, denitrification consists of progressive reduction of nitrate to nitrogen gas (N_2; Henze et al., 1995). Appropriate aerobic:anoxic conditions and BOD_5:N influent ratio (i.e., > 3; Osada et al., 1991) are determinant factors for achieving satisfactory N-removal efficiency. Alternation of aerobic and anoxic conditions can be achieved spatially using specifically dedicated tanks including internal recirculation (Vanotti et al., 2009), or temporally using a single tank under intermittent aeration (Osada et al., 1991). Thus, while the former essentially requires separate tanks, the latter requires control of the aeration time.

Alternatively, N-removal under continuous aeration and micro-aerobic conditions, with low dissolved oxygen (DO) concentration, is also possible owing to simultaneous nitrification and denitrification (SND). This strategy was tested in the early stages of research for the treatment of swine wastewater using a continuously aerated chemostat-type reactor such as a continuous stirred-tank reactor (CSTR) without biomass recirculation (Smith and Evans, 1982). More recently, this method has been employed using other engineered systems such as a sequencing batch reactor (SBR) and an upflow reactor among others (Jia et al., 2012; Meng et al., 2015; Third et al., 2003). Interesting examples concerning the use of single low-aerated CSTRs in swine wastewater treatment can be found in studies such as Smith and Evans (1982), who confirmed 45% t-N removal at DO levels as low as 1% of saturation (0.088 mg DO/L), and Béline et al. (1999), who reported 66% t-N removal under a redox potential of 0 mV. Moreover, limited aeration in the bioreactor may prompt the enrichment of autotrophic anaerobic ammonium oxidation (anammox, AMX) bacteria in the long term (Magrí et al., 2013; Suto et al., 2017). In contrast to the conventional approach based on the sequential coupling of complete nitrification and denitrification processes, the implementation of SND may help to reduce the cost of treatment owing to a decrease in energy consumption needed for aeration. However, low DO concentrations affect the metabolic pathways leading the process and may result in increased emissions of N_2O (Kong et al., 2016). A detailed characterization of the SND process under particular constraints is therefore of great importance.

Mathematical modelling is an interesting tool for studying wastewater treatment processes aiming to remove nutrients. Several activated sludge models (ASMs) available in the literature (Henze et al., 2000) have largely been applied in the field of municipal wastewater. However, alternative developments are necessary when dealing with highly concentrated streams. In this regard, the use of modelling for characterizing swine wastewater treatment has not often been considered. Béline et al. (2007a,b) proposed an extended version of the ASM1 including nitrite as intermediate of both the nitrification and denitrification processes. Alternatively, Magrí and collaborators (Magrí and Flotats, 2008; Magrí et al., 2009) proposed a revised version of the ASM2 including nitrite as the intermediate, free ammonia (FA, NH_3) and free nitrous acid (FNA, HNO_2) as potential inhibitors in nitrification, pH as the state variable, and temperature as the process parameter. Both models were calibrated using data obtained from pilot-scale SBRs. The use of these models for analyzing the SND process can help to its understanding.

The aim of this study was to characterize the SND process when treating swine wastewater. Two bench-scale AS systems were operated under different DO conditions at three temperatures: high DO at 1.5–2.5 mg/L and low DO at < 0.1 mg/L, at 10, 20, and 30 °C. The experimental results were used subsequently in a simulation study in which a revised version of the model proposed by Magrí and Flotats (2008) was applied. The effect of the DO on the N removal process was then numerically assessed.

2. Materials and methods

2.1. Description of bench-scale activated sludge systems

Two bench-scale CSTRs operated as AS bioreactors, AS1 and AS2 (Fig. 1a), were run under different aeration conditions of high DO and low DO, respectively, to assess the effect of the DO concentration on their performances. Such continuously aerated tanks, with 0.9 L for the water phase, were followed by a settler of 0.15 L, where the sludge was allowed to decant, and were then returned to the bioreactor. Furthermore, excess sludge was withdrawn from the system as required. The aeration rate was manually controlled to fit DO concentrations of 1.5–2.5 mg/L (typical conditions) and about 0.1 mg/L (limiting conditions) for AS1 and AS2, respectively. The DO concentration in the liquid bulk was monitored by using a specific probe (HQ30d and LDO 1010, Hach Co., USA). The volumetric loading rate applied to the reactors was adjusted to 0.52 g BOD_5/(L d). Table 1 shows the operational conditions for the AS reactors. During the experimental period, both bioreactors were placed in a thermostatic chamber where the temperature was sequentially adjusted to 20 °C for days 1–46 (run 1), 10 °C for days 47–76 (run 2), and 30 °C for days 77–108 (run 3). For calculations, stable operating conditions were assumed in days 34–46 (run 1), 63–76 (run 2), and 104–108 (run 3). Further details are given in Appendix A (S-1).

2.2. Influent swine wastewater preparation

The influent used to feed the AS bioreactors was prepared by mixing wastewater collected in a swine barn located at the facilities of NARO (Japan), preconditioned swine feces, NH_4Cl, and $KHCO_3$. Targeted BOD_5 and NH_4^+-N contents of the mixture were 2000 and 500 mg/L,