Journal of Environmental Management 177 (2016) 202–212

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Complete reduction of highly concentrated contaminants in piggery waste by a novel process scheme with an algal-bacterial symbiotic photobioreactor

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ARTICLE INFO

Article history:
Received 9 October 2015
Received in revised form
8 April 2016
Accepted 9 April 2016
Available online 18 April 2016

Keywords:
Piggery waste
ATAD
EGSB
Algal polishing
Vertical photobioreactor

ABSTRACT

The complete reduction of highly concentrated contaminants in piggery waste was achieved with an innovative process scheme consecutively combining autothermal thermophilic aerobic digestion (ATAD), an expanded granular sludge bed (EGSB) and a microalgal-bacterial symbiotic vertical photobioreactor (VPBR), followed by biomass recycling for effluent polishing. Contaminants in piggery waste, such as high organic and inorganic matter, total nitrogen (TN), and total phosphorus (TP) contents, were successfully reduced in the newly implemented system. The concentrations of volatile solids (VS) and the chemical oxygen demand (COD) for organic matter in the feed were reduced by approximately 99.3% and 99.7%, respectively, in the innovative system. The overall reduction efficiencies in TN, ammoniacal nitrogen, and TP were 98.8, 98.4, and 93.5%, respectively, through ammonia gas emission, coagulated sludge disposal, and the algal-bacterial symbiotic polishing process. Fecal coliform density was decreased to $<1.7 \times 10^4$ CFU g^{-1} total solids. Biogas and CH_4 in the EGSB were generated in the range of 0.36–0.79 and 0.18–0.44 L g^{-1} [VS removed], respectively, and contained 245 ± 19 ppm (v/v) [H_2S].

1. Introduction

Intensive pig farming has led to the excessively increased generation of piggery waste, which has resulted in the over-application of manure as an organic fertilizer in land-restricted regions and pollution in water and agricultural soil (Bernet and Béline, 2009). Thus, the excessive application of piggery waste as a fertilizer should be limited, and alternative treatment solutions are often required due to uncontrolled exposure of nutrients to the water environment (Riaño and García-González, 2014). Therefore, for sustainable solutions to a persistent problem from intensive pig farms in smaller areas, a great deal of research effort to reduce highly concentrated organic matter, phosphorus, and nitrogen contaminants in piggery waste has been expended to implement more efficient alternative treatment systems (Lopez-Fernandeza et al., 2011; Ippersiel et al., 2012; Riaño and García-González, 2014). One solution is to enhance the synergistic relationship between microalgae and bacteria to utilize algal-bacterial symbiosis during the secondary or tertiary treatment of piggery waste in photobioreactors (Arbib et al., 2014).

The autothermal thermophilic aerobic digestion (ATAD) process previously showed effective reduction efficiencies in volatile suspended solid removal, pathogen levels, and 60–70% of the total nitrogen in raw piggery waste (Béline and Martinez, 2002; Kelly and Mavinic, 2003; Park et al., 2010). The expanded granular sludge bed (EGSB) reactor improves mixing and contact with a higher superficial velocity (Lopez-Fernandeza et al., 2011). The combined process, consisting of a faster aerobic thermophilic stage and a slower anaerobic mesophilic stage, showed more efficient organic matter reduction and pathogen control (Karakashev et al., 2008). Consequently, a hybrid multi-stage process (HMUS) of the ATAD and EGSB system may be one feasible alternative to treat highly concentrated piggery waste slurry (Lee and Han, 2012).

In the symbiotic assimilative process, bacteria produce CO_2 required by microalgae for photosynthesis, whereas microalgal photosynthesis generates the O_2 needed for the bacteria to oxidize both organic matter and NH_4^+. Piggery waste contains highly excessive concentrations of inorganic and organic compounds and

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http://dx.doi.org/10.1016/j.jenvman.2016.04.025

other nutrients, which provide a strongly pertinent potential of suitable cultivation conditions necessary for a high algae growth rate and nutrient removal efficiency. Thus, excessive contaminants in piggery waste are efficiently reduced via symbiotic assimilation into the algal-bacterial biomass. Cultivating algae in waste streams provides various benefits, including nutrient reduction, wastewater treatment, and CO_2 fixation, over traditional algae ponds. Consequently, incorporating wastewater treatment with algal-bacterial symbiosis may present an economically feasible and environmentally friendly process for sustainable algal-bacterial wastewater treatment (Wang et al., 2010a,b; Zhou et al., 2012).

The strategies are based on the feasible combination of the selected processes that can be implemented and are necessary for each specific requirement. In this context, the potential of microalgae to simultaneously reduce carbon (C), nitrogen (N) and phosphorus (P) via mixotrophic assimilation contributes an important mechanism to the enhancement of nutrient recovery compared with aerobic or anaerobic conventional processes (Arbib et al., 2014). The development of an innovative process configuration to simultaneously enhance both nutrient reduction and the harvesting of biomass is required to implement sustainable microalgal-bacterial piggery waste treatment systems. Thus, polishing of the high nutrient content of piggery waste specifically leads to the vertical photobioreactor configuration with biomass recycling to rapidly settle the algal-bacterial population based on nutrient removal (De Godos et al., 2014).

The potential of a microalgal-bacterial symbiotic system for nutrient removal has been previously documented, but not for the type of system tested in this study. Thus, the previously reported and successful performance of the vertical photobioreactor configurations and the mechanisms in microalgal-bacterial symbiotic cultures for efficient C, N, P and VS removal during the treatment of piggery waste were evaluated for the implementation of an innovative system, such as the polishing process of the secondary effluent with the symbiotic vertical photobioreactor for tertiary treatment of piggery waste. This study proposed a novel concept for sustainable piggery waste treatment with a comprehensive assessment of the efficiency. Thus, this work will be beneficial for future practical applications. The aim of this study was to demonstrate the ability and efficiency of the innovative process scheme using the ATAD and EGSB process incorporated with a vertical photobioreactor (VPBR), followed by biomass recycling for the reduction of excessively concentrated contaminants in piggery waste. The specific objectives were to determine (1) the system performance of the first and second stage unit systems with regard to the reduction of volatile solids (VS), the supernatant chemical oxygen demand (COD), total nitrogen (TN), ammonium nitrogen (NH_4^+–N), and total phosphorus (TP); (2) the system performance of VPBR; (3) the overall mass balance for the system for each unit process; (4) fecal pathogen reduction; and (5) biogas production during piggery waste treatment.

2. Materials and methods

2.1. Overall process scheme of the experiments

The experiments were conducted to explore the effectiveness of reducing excessively concentrated organics and nutrients from piggery waste. A schematic process diagram of the experimental set-up is presented in Fig. 1. The experimental process was operated in a three-stage mode of consecutive unit systems (i.e., in a series) by adopting the effluent from the previous stage and applying it to the next stage as the influent. Thus, the first stage was composed of the unit systems of the ATAD and coagulation. The second stage consisted of the unit systems of organic acid feeding and the EGSB. The vertical photobioreactor (VPBR) with biomass recirculation was coupled to the system as the third stage for polishing the effluent from the EGSB (Fig. 1).

The ATAD and EGSB reactors were cylindrical tanks of the ATAD (200 mm ø × 750 mm h) and the EGSB (90 mm ø × 1150 mm h), with working volumes of 18.0 and 4.0 L, respectively. The VPBR (90 mm ø × 1150 mm h), with a working volume of 4.0 L, was constructed of cylindrical transparent polycarbonate. An Imhoff cone with a volume of 2 L was connected to the outlet of the VPBR for settling, and the microalgal-bacterial biomass was recirculated from the bottom of the Imhoff cone into the VPBR at 0.3–0.5 L d^{-1}. Air was blown into the ATAD reactor by a torus air blower to sustain oxygen concentrations of 2.5–3.5 mg L^{-1}, which were needed to promote heat generation through metabolic oxidation of the organic matter.

2.2. Process description and operating conditions

The inflow of piggery waste from a local community raising 6000 hogs in Seosan-si Chungcheongnam-do, Korea, was supplied to the experimental system. The inflow feeding piggery waste was composed of sludge mixtures of feces, urine and wash water. Table 1 shows the characteristics of feeding piggery waste, and its composition was monitored for approximately 400 days. Triplicate samples were analyzed in each sampling twice per week.

The first stage of the system with the ATAD and coagulation was operated in batch mode at 3-day hydraulic retention time (HRT) with 18.0 L of piggery waste mixed with 20 mL of enrichment medium of *Bacillus* and kept at 55 ± 1 °C. Coagulation was conducted by transferring a portion of the treated piggery waste withdrawn from the ATAD into the coagulation tank. The top suspensions were settled with the addition of 500 mg L^{-1} of coagulant (Califloc; Outriger Co., Seoul, Korea) and 75 mg L^{-1} of high molecular flocculent (cation-polymer) into the coagulation tank. Thus, the coagulated sludge was separated from the supernatant by high speed centrifugation, and then the supernatant was sent to the organic acid tank, which was placed as a storage tank to prevent shock organic loading into the EGSB reactor.

The EGSB, the second stage unit system in the treatment system, was inoculated with 2.0 L (50% of the reactor working volume) of mesophilic granular sludge adopted from a UASB reactor at the sewage treatment plant. During the three weeks following the inoculation of the EGSB, the granular sludge in the EGSB was augmented to formulate 11.5 g [TS] L^{-1} and 7.5 g [VS] L^{-1}. Feeding the supernatant from the organic acid tank to the EGSB was continuously conducted using a centrifugal pump at a flow rate of 1 L d^{-1}. The granular sludge bed in the EGSB was fluidized by effluent recirculation to sustain an adequate up-flow superficial velocity. During the start-up, the organic loading rate (OLR) was gradually increased from 6.0 kg COD m^{-3} d^{-1} and sustained at a maximum of 20.85 kg COD m^{-3} d^{-1}. The linear up-flow superficial velocity was also increased from 0.7 m h^{-1} and maintained at a maximum of 2.8 m h^{-1} during operation. The EGSB reactor was also maintained under the mesophilic condition (35 ± 1 °C) and buffered by alkaline compounds ($NaCO_3$, $NaHCO_3$, and $Ca(OH)_2$) at pH 7.3–7.9 to enhance the growth of the anaerobic bacteria. Evaluation of the experimental systems started 30 days after the initial operation and prior to data collection. Table 2 shows the operating parameter conditions of all of the proposed systems.

2.3. Culture condition and the symbiotic microalgal-bacterial VPBR

The VPBR was the third stage unit system for nutrient reduction. An enclosed cylindrical transparent polycarbonate reactor (VPBR) with a total working volume of 4.0 L was utilized to reduce residual