Journal of Environmental Management 222 (2018) 155–163

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Optimization of rotational speed and hydraulic retention time of a rotational sponge reactor for sewage treatment

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ARTICLE INFO

Keywords:
Rotational sponge reactor
Rotational speed
Hydraulic retention time
Optimization
Sewage treatment

ABSTRACT

A rotational sponge (RS) reactor was proposed as an alternative sewage treatment process. Prior to the application of an RS reactor for sewage treatment, this study evaluated reactor performance with regard to organic removal, nitrification, and nitrogen removal and sought to optimize the rotational speed and hydraulic retention time (HRT) of the system. RS reactor obtained highest COD removal, nitrification, and nitrogen removal efficiencies of 91%, 97%, and 65%, respectively. For the optimization, response surface methodology (RSM) was employed and optimum conditions of rotational speed and HRT were 18 rounds per hour and 4.8 h, respectively. COD removal, nitrification, and nitrogen removal efficiencies at the optimum conditions were 85%, 85%, and 65%, respectively. Corresponding removal rates at optimum conditions were 1.6 kg-COD $m^{-3}d^{-1}$, 0.3 kg-NH_4^+-N $m^{-3}d^{-1}$, and 0.12 kg-N $m^{-3}d^{-1}$. Microbial community analysis revealed an abundance of nitrifying and denitrifying bacteria in the reactor, which contributed to nitrification and nitrogen removal.

1. Introduction

A sewage treatment process should meet effluent standards to protect the environment whilst being economically feasible. Therefore, energy conservation is an essential aspect of sewage treatment. To achieve tighter effluent standards, current mainstream technologies, such as activated sludge processes, are mainly dependent on extending aeration time (Hassard et al., 2014). Currently, approximately 50% of the energy consumption in the sewage treatment is used for aeration, which is likely to be increased further (McCarty et al., 2011) Hence, a sewage treatment process that can simultaneously produce high effluent quality and energy conservation will be an excellent option for sewage treatment. Rotating biological contactors (RBC) are considered as such a treatment process due to their ability to remove organic matter and nitrogen while also providing low operational cost, compactness, easy operation, and a small ecological footprint (Patwardhan, 2003; Tawfik et al., 2006). However, few shortcomings of RBCs are noteworthy, such as limited attachment area and a low oxygenation capacity, due to the use of disc media (Mathure and Patwardhan, 2005). Moreover, the effectiveness of the organic and nitrogen removal processes is strictly associated with the oxygenation capacity of RBCs during treatment (Kubsad et al., 2004).

To overcome these shortcomings, a modified rotational system called a rotational sponge (RS) reactor, with superior oxygenation capacity compared to conventional RBCs was developed. Subsequently, the RS reactor was operated to evaluate its nitrification capability by using inorganic synthetic wastewater. The RS reactor achieved 97% nitrification efficiency at a hydraulic retention time (HRT) of 16 h (h) at the rotational speed of 10 rounds per hour (rph), without external aeration (Hewawasam et al., 2017). Even though nitrification was successfully achieved, organic removal was not studied in the previous study. Therefore, analyzing the overall performance of the reactor is important, before the applying for sewage treatment. Furthermore, it is recognized the need of optimizing key operational factors such as rotational speed and HRT to improve the operational efficiency of the reactor, when it is further developed into such actual application for sewage treatment.

There are several methods to optimize the key operational factors in a reactor. Most studies use an experimentation method, in which a single factor is varied while other factors are fixed at specific values

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https://doi.org/10.1016/j.jenvman.2018.05.046
Received 29 March 2018; Received in revised form 9 May 2018; Accepted 15 May 2018
0301-4797/

(Ölmez, 2009). This approach fails to demonstrate the effects of interaction among factors and responses, and it consumes longer time periods (Hasan et al., 2011). Therefore, this study adopts response surface methodology (RSM), a recently evolved technique to optimize the performance of complex systems based on statistical design of experiments (DOE) (Muhamad et al., 2013). Moreover, through RSM, it is possible to design experiments, to build models, and to analyze optimal conditions of the factors that provide desirable responses with a reduced number of experiments (Ahmad et al., 2007).

The objective of this study is to evaluate the optimum conditions of rotational speed, HRT, and the process performance with regard to organic removal, nitrification, and nitrogen removal using synthetic wastewater similar to sewage. Initially, in this study, an experimental design was arranged as per the RSM, using Design Expert 10 software. Subsequently, a pilot scale RS reactor was operated using according to experimental design. Afterward, based on the experimental results, models for organic removal, nitrification, and nitrogen removal were built and optimum conditions of rotational speed and HRT were assessed. Lastly, microbial community structure at optimum conditions of rotational speed and HRT was analyzed using sequence analyses based on the 16S rRNA gene.

2. Materials and methods

2.1. Pilot scale RS reactor and its operation

A pilot scale RS reactor was designed with a rotating wheel, polyurethane sponges and a water tank (Fig. 1). The diameter and the width of the rotating wheel were 2 m and 0.25 m, respectively. It was separated into 8 partitions, and each partition was further compartmentalized into two layers, named “outer” and “inner”. Partitions were packed with G3-type polyurethane sponges, with a sponge volume of 110 L. The water tank had a diameter of 2.4 m, a width of 0.5 m, an immersion level of 15%, and a wastewater volume of 90 L. Rotational speed of the RS reactor was controlled through a speed control meter. The reactor was inoculated using seed sludge obtained from a conventional, activated sludge process (ASP), located at the sewage treatment center in Nagaoka, Japan. In this study, the RS reactor was used to resemble the post-treatment unit of primary sedimentation tank in the actual sewage treatment process. Accordingly, synthetic wastewater was prepared to simulate the effluent conditions of primary sedimentation tank, which contains COD, NH_4^+-N, and TN concentrations of 200 mgL^{-1}, 35 mgL^{-1}, and 35 mgL^{-1}(Carballa et al., 2004; Tandukar et al., 2007). The synthetic wastewater consists of sodium acetate (0.15 gL^{-1}), glucose (0.05 gL^{-1}), NH_4Cl (0.12 gL^{-1}), $NaHCO_3$ (1.44 gL^{-1}), KH_2PO_4 (0.14 gL^{-1}), and K_2HPO_4 (3.5 gL^{-1}). This was prepared in a separate tank on a daily basis and pumped to the reactor, using a peristaltic pump. Temperature and pH were maintained at 30 °C and 8, respectively. During the operational period, the concentration of COD, NH_4^+-N, NO_3^--N, and NO_2^--N of both influents and effluents were measured frequently.

2.2. Water quality analysis

The concentrations of NH_4^+-N, NO_3^--N, and NO_2^--N in influent and effluent were routinely measured by ion chromatography (Hewawasam et al., 2017). COD was analyzed using an HACH water quality analyzer (HACH DR4000). pH was measured on-site using a portable pH meter (TPX- 999Si- TOKO, Japan). All other analytical procedures were performed according to the standard methods (APHA/AWWA/WEF, 2012).

2.3. Experimental design for optimization

In this study, RSM was used to assess the relationships among three responses (i.e., removal of organic, ammonium, and nitrogen) and the associated operating factors (rotational speed and HRT), as well as to optimize these factors to predict the best responses. A three-level factorial design (Box and Behnken, 1960; Saccani et al., 2005) was employed to determine the experimental procedure for this study. Factors and levels used in the three-level factorial design are shown in Table 1. The number of experiments required for this design is calculated by the expression $N = 3^k$, where N is the experiment number, and k is the factor number (Bezerra et al., 2008). Total numbers of experiments with two factors were 12 ($=3^2$), where nine experiments were enhanced with three repetitions at the design center to assess the pure error. An appropriate model for predicting the optimal conditions of factors can be described by the following quadratic model form (Darvishi Cheshmeh Soltani et al., 2014; Muhamad et al., 2013):

$$Y= \beta_0 + \sum_{j=1}^{k} \beta_j X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + \sum_{i} \sum_{<j=2}^{k} \beta_{ij} X_i X_j \tag{1}$$

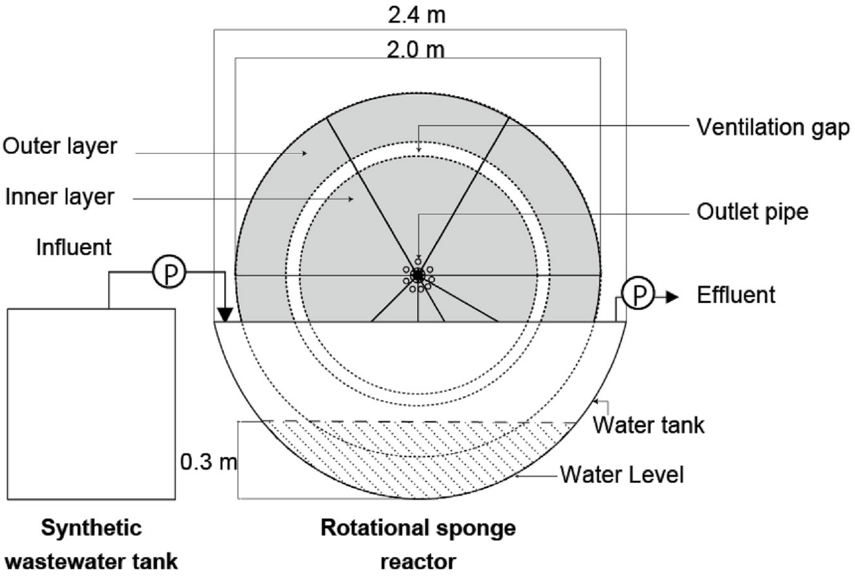

Fig. 1. Schematic diagram of the RS reactor used in this study. Gray color represents the distribution of the sponges in the outer and inner layers. Ventilation gap allows air to pass through the outer and inner layers while rotation of the reactor.