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Autotrophic nitrogen removal over nitrite in a sponge-bed trickling filter

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HIGHLIGHTS

- Anammox process under natural air convection is feasible in sponge-bed reactors.
- Nitrogen removal was consequence of coexistence of nitrifiers and anammox bacteria.
- Oxygen from the influent and the air governed the performance of the reactors.
- Sponge-bed reactors showed robustness to the nitrogen loading rate fluctuations.
- A nitrogen removal of 52–54% was reached in only 100 days and 1.71–2.96 h of HRT.

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ABSTRACT

Partial nitritation in sponge-bed trickling filters (STF) under natural air circulation was studied in two reactors: STF-1 and STF-2 operated at 30 °C with sponge thickness of 0.75 and 1.50 cm, respectively. The coexistence of nitrifiers and Anammox bacteria was obtained and attributed to the favorable environment created by the reactors' design and operational regimes. After 114 days of operation, the STF-1 had an average NH_4^+-N removal of 69.3% (1.17 kg N/m^3_{sponge} d) and a total nitrogen removal of 52.2% (0.88 kg N/m^3_{sponge} d) at a Nitrogen Loading Rate (NLR) of 1.68 kg N/m^3_{sponge} d and Hydraulic Retention Time (HRT) of 1.71 h. The STF-2 showed an average NH_4^+-N removal of 81.6 % (0.77 kg N/m^3_{sponge} d) and a total nitrogen removal of 54% (0.51 kg N/m^3_{sponge} d), at an NLR of 0.95 kg N/m^3_{sponge} d and HRT of 2.96 h. The findings suggest that autotrophic nitrogen removal over nitrite in STF systems is a feasible alternative.

1. Introduction

Upflow Anaerobic Sludge Blanket (UASB) reactors have been recognized as suitable sewage treatment processes in developing countries because of their low energy use, easy maintenance and cost-effectiveness. Several full-scale examples can be found worldwide for sewage treatment (Chernicharo et al., 2012). However, anaerobic wastewater treatment systems cannot remove nutrients and their effluents usually do not comply with the required discharge standards that apply to the receiving water bodies. Therefore, suitable post-treatment processes are required to be installed after UASB treatment. Anammox bacteria have opened the possibility to achieve cost-effective biological nitrogen removal from municipal wastewater when coupled with UASB reactors. Nevertheless, an important technical challenge to sustain the Anammox process is the required partial nitritation to supply ammonium (NH_4^+-N) and nitrite (NO_2^--N) in the appropriate ratio to the biomass. Moreover, for the envisaged application, the foreseen technology should not depend on mechanical aeration, as this will add to the complexity and costs. In previous research (Sánchez Guillén et al., 2015), was proved that Anammox bacteria could be sustained in closed sponge-bed trickling filters (CSTFs). The next step for developing an appropriate low cost reactor system for N removal is including partial nitritation by ammonia oxidizing organisms (AOO) into the sponge-bed biomass. Uemura et al. (2011) reviewed that, so far, partial nitritation research is focused

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on (i) reactors operated at 30–40 °C, (ii) reactors operated at high salinity concentrations, (iii) the application of mechanically controlled low dissolved oxygen (DO) concentrations, (iv) high inorganic carbon content effluents, (v) the inhibition of nitrite oxidizing organisms (NOO) by free ammonia or free nitrous acid, and (vi) a combination of the previous factors. A thorough list of full-scale facilities achieving partial nitritation, by means of some of the above parameters, and the Anammox process for side-stream treatment is described elsewhere (Lackner et al., 2014).

The down-flow hanging sponge (DHS) reactor has been developed for post-treatment of UASB effluents as an affordable, easy-maintenance and promising sewage treatment for developing countries (Machdar et al., 2000; Tandukar et al., 2006). The DHS reactor is a sponge-based trickling filter that uses polyurethane sponge that hangs freely in the air as support media to retain biomass. The oxygen in the air is dissolved into the trickling wastewater from the top of the reactor providing the required DO for the growth of microorganisms retained both inside and outside the sponge media. Therefore, no external aeration is needed. Furthermore, Tandukar et al. (2006) demonstrated that the UASB–DHS system has produced excellent results to remove COD, BOD and to some extent nitrogen from sewage.

By applying a closed DHS reactor for NH_4^+ rich synthetic wastewater (100 mg NH_4^+-N/L) under controlled oxygen conditions using an air pump, Chuang et al. (2007) attained partial nitritation achieving about 50% ammonium conversion to nitrite at 0.2 mg/L of DO and 30 °C. Though promising, this application requires mechanical control equipment to control the DO in the reactor, and therefore elevated capital investment, high operational costs and advanced technical expertise. On the other hand, the use of a sponge-based trickling filter unit with natural air convection, being the DHS reactor the major and most important example of such system; could be a promising and cost-effective approach as a preliminary treatment step for the Anammox process to achieve partial nitritation of ammonium rich UASB effluents. In this regard, Machdar et al. (2000) observed in a DHS reactor a DO gradient from 7.5 mg O_2/L in the external layers of the sponge to around 0.2 mg O_2/L in the inner layers (1 cm inside the sponge). Such DO conditions may be favorable to sustain partial nitritation in sponge-bed filters (Chuang et al., 2007). Moreover, sponge-based trickling filters possess other advantageous properties such as (i) a large surface area that can lead to an increased biomass retention capacity, thus being able to attain long solids retention times (SRT) favorable for slow growing organisms, (ii) potentially high microbial conversions as a consequence of the high biomass retention and high permeability which could be reflected in shorter hydraulic retention times, (iii) presumably low construction costs and low space requirements, and (iv) low operational costs, since no mechanical aeration and less complicated control equipment would be required.

This research aims to assess the feasibility to attain partial nitritation with natural air convection in lab-scale sponge bed trickling filters as a low cost post-treatment step using a synthetic substrate that simulates an ammonium rich effluent (100 mg of NH_4^+-N/L) from a UASB system treating municipal wastewater at 30 °C. Suitable operational parameters, such as sponge thickness, NLR and HRT, are also explored towards the development of a cost-effective autotrophic nitrogen removal process over nitrite in sponge bed trickling filter systems.

2. Methods

2.1. Design of the reactors

The partial nitritation was carried out in two lab-scale flow-through type Sponge-bed Trickling Filter (STF) units (namely STF-1 and STF-2). The trickling filter units were constructed using transparent acrylic glass. Horizontally layered polyurethane sponge slabs BVB Sublime (second generation) (BVB Substrates; De Lier; The Netherlands) were used as biomass support media. The thickness of the sponge support material was chosen taking into account the studies of Araki et al. (1999) who demonstrated that the sponge material maintains aerobic conditions down to the depth of 0.75 cm from the surface, beyond which is an anoxic environment, and the studies of Machdar et al., 2000 who observed a DO concentration of 0.2 mg O_2/L at 1.0 cm inside the sponge from surface. Thus, the sponge sheet thickness was 0.75 and 1.50 cm for STF-1 and STF-2, respectively. The configuration of the two reactors is summarized in Table 1 and Fig. 1 illustrates a schematic diagram of each reactor.

Table 1
Configuration of the two lab scaled Sponge-bed Trickling Filters.

Parameter (unit)	STF-1	STF-2
Overall Reactor height (cm)	60.5	46.0
Effective Reactor height (cm)	54	39
Reactor shaft size – internal (cm^2)	6.75 × 6.75	6.75 × 6.75
Sponge sheet size (cm^2)	6.75 × 6.75	6.75 × 6.75
Sponge sheet thickness (cm)	0.75	1.50
Sponge void ratio (%)	98	98
Sponge density (kg/m^3)	28	28
Number of sponge layers	29	15
Total sponge volume (cm^3)	991	1025
Specific surface area (m^2/m^3)[a]	326	193
Spacing between sponge layers (cm)	1.0	1.0
Volume fraction of sponge medium (%)	37	47

[a] Based on the total number of sponge sheets per reactor, the surface area of each sponge sheet and the total volume of sponge sheets.

Both reactors were operated with natural air convection at 30 °C in a temperature controlled room. Air circulation across sponge medium was facilitated through lateral openings located above each sponge layer. All openings (diameter of 4 mm) were kept open at the start-up phase to ensure nitritation and, in a step wise manner, gradually closed in order to reach low dissolved oxygen (DO) concentrations, i.e. below 2 mg/L, across certain sponge layers to attain partial nitritation. In some occasions during the experimental period, the mentioned lateral openings were partly re-opened to provide additional oxygen. To limit air circulation over the height of the reactor, the sponge layers had the same cross-sectional area as the reactor's surface area. Synthetic wastewater was fed from the top of each reactor with a miniature water distributor (shower). To minimize the influent DO concentrations, the demineralised water, by far having the largest share of the synthetic wastewater, was periodically flushed with nitrogen gas. In addition, an oxygen scavenger water lock, containing sodium sulphite and cobalt chloride, was installed in the ventilation located on top of the demineralized water tank.

2.2. Synthetic wastewater

Synthetic wastewater was composed of two solutions divided in two containers (Fig. 1). The composition of these substrates per 1 L of demineralized water was (modified from van de Graaf et al., 1996) (i) in the ammonium-rich feed: 5.9656 g NH_4Cl; 0.77 g $MgSO_4 \cdot 7H_2O$; 0.3906 g KH_2PO_4; 4.6875 g $CaCl_2 \cdot 2H_2O$; and, (ii) in the bicarbonate feed: 0.1786 g $FeSO_4 \cdot 7H_2O$; 19.531 g $KHCO_3$; 0.1786 g NaEDTA and 1.25 mL of trace element solution. The trace element solution contained per liter: 15 g EDTA; 0.43 g $ZnSO_4 \cdot 7H_2O$; 0.24 g $CoCl_2 \cdot 6H_2O$; 0.99 g $MnCl_2 \cdot 4H_2O$; 0.25 g $CuSO_4 \cdot 5H_2O$; 0.22 g $Na_2MoO_4 \cdot 2H_2O$; 0.19 g $NiCl_2 \cdot 6H_2O$; 0.1076 g Na_2SeO_4; 0.014 g H_3BO_3; 0.05 g $NaWO_4 \cdot 2H_2O$. After mixing the solutions with demineralized water, the NH_4^+-N concentration in the synthetic wastewater was approximately 100 mg/L with a pH of about 7.8.