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Low-strength wastewater treatment in an anammox UASB reactor: Effect of the liquid upflow velocity

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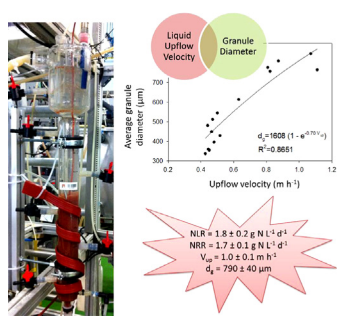
HIGHLIGHTS

- Stable anammox operation of low-strength wastewater was achieved in an UASB reactor.
- High nitrogen removal rates were obtained compared to other similar systems.
- Liquid V_{up} presented a direct but not immediate effect on the anammox granulation.
- Low liquid V_{up} allowed a successful anammox operation in an UASB reactor.
- Low liquid V_{up} led to mass transfer limitations in an UASB reactor.

GRAPHICAL ABSTRACT



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ABSTRACT

Two-stage systems have been proposed to overcome the drawbacks associated to the implementation of the autotrophic biological nitrogen removal process in the mainstream of urban wastewater treatment plants. In this study, an upflow anammox sludge blanket (UAnSB) reactor was successfully operated for 325 days treating a low-strength synthetic influent mimicking mainstream conditions. A nitrogen loading rate of up to 1.8 ± 0.2 g N L^{-1} d^{-1} was achieved at 26 °C and the nitrogen removal rate obtained (1.7 ± 0.1 g N L^{-1} d^{-1}) resulted considerably higher than most of the previously reported values for systems treating low-strength wastewater at similar temperatures. Fluorescence *in situ* hybridization analysis showed a high enrichment in the anammox specie *Candidatus Brocadia anammoxidans* during the whole operation. The evolution of the granule diameter was followed throughout the operation of the UAnSB reactor and a direct correlation of the average granule diameter with the liquid upflow velocity (V_{up}) was established, being the higher the V_{up}, the bigger the granules. A stable granule diameter of 790 ± 40 µm was achieved by maintaining a V_{up} of 1.0 ± 0.1 m h^{-1}. The low V_{upS} applied avoid the use of effluent recirculation which would present a huge inconvenient to implement UAnSB reactors at real scale, however these low V_{upS} led to external mass transfer problems in the reactor. In spite of the mass transfer limitations, not only a high specific anammox activity (0.26 ± 0.02 g N g^{-1} VS d^{-1}) was achieved in the UASB reactor but also a high nitrogen removal (80 ± 3%).

1. Introduction

The implementation of the autotrophic biological nitrogen removal (BNR) in the mainstream of urban wastewater treatment

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plants (WWTPs) has been proposed as the main alternative for achieving a neutral energy-consumer or even an energy-producer urban WWTP [1,2]. The neutral energy-consumer urban WWTP is based on the use of most of the entering organic matter to produce biogas (with the subsequent energy recovery) plus the reduction of aeration costs due to the lower oxygen requirements of the autotrophic BNR compared to the conventional BNR through nitrification and heterotrophic denitrification. Hence, it consists of a first step of high-rate organic matter removal and a second step of autotrophic BNR where the effluent of the first step is treated through the partial nitritation and anaerobic ammonium oxidation (anammox) processes.

The autotrophic BNR can be implemented either in one single reactor (one-stage systems) or in two separated reactors (two-stage systems). Recently, many studies were focused on the implementation of autotrophic BNR treating low-strength wastewater by using one-stage systems [3–7], however these systems present some significant disadvantages: (i) low nitrogen removal rates achieved; (ii) destabilization of the partial nitritation in the long term; and (iii) competition for nitrite of nitrite oxidizing bacteria (NOB) and anammox bacteria with the subsequent destabilization of anammox process. Thus, the two-stage strategy has appeared as an alternative to overcome these problems, since allows a more stable performance and control of the partial nitritation and anammox processes [8–11].

The application of the anammox process at mainstream conditions (low-strength and low temperature) appears as a prerequisite for the implementation of a two-stage system for autotrophic BNR in urban WWTPs. Thus, many efforts have been made to achieve a successful start-up and operation of anammox reactors treating mainstream wastewater [12–16]. The main disadvantage of anammox process is the very long doubling time (10–12 days) of the anammox bacteria [17,18]. This slow growth is even more troublesome at mainstream conditions because of (i) the low biomass growth rate due to the operation temperature under the optimum range and (ii) the low net biomass production due to the low nitrogen content of the stream [19]. Therefore, a high solids retention time (SRT) is needed to increase the biomass concentration in the system and guarantee the growth of anammox at mainstream conditions.

One efficient alternative to achieve a high SRT is the use of granular sludge [20–22]. Different reactor configurations have been proposed for achieving granular sludge under anaerobic conditions: sequencing batch reactors (SBRs), filters, expanded bed and fluidized bed reactors, among others [23]. However, the use of Upflow Anaerobic Sludge Bed (UASB) reactors appear as the most attractive alternative for the implementation of anammox process [24–26]. The main advantage over other reactors is that UASB reactors present a high biomass retention capacity which allows achieving extremely high loading rates, and furthermore, the requirements of area and reactor size are low. However, UASB reactors usually operate at upflow velocities as low as 0.5–1.5 m h^{-1} [27,28], which can trigger to external mass transfer limitations due to the lack of efficient mixing in the sludge bed.

Biomass granulation is a complex process that can be affected by different factors; either physical and chemical factors related to the process conditions applied, or even biological factors such as the cell-to-cell communication (quorum sensing) [23]. The selection pressure imposed on the sludge is one of the factors affecting granulation. Thus, the selection pressure theory hypothesizes that granulation process strongly depends on the continuous selection of sludge particles that occurs in the reactors, in such a way that high selection pressure would wash-out light and dispersed sludge while heavier sludge could be retained in the system [23,24]. The selection pressure may result from any environmental condition, such as temperature, pH, hydraulic retention time, upflow velocity (V_{up}), reactor configuration, etc. In the case of UASB reactors, selection pressure generally depends on the liquid V_{up} and gas production, which affect to the shear force imposed to biomass. Thus, high liquid V_{upS} lead to high hydrodynamic shear forces which enhance the granulation process [29,30].

Hence, to overcome the limitations associated to UASB reactors (specifically external mass transfer problems), a variant of UASB reactors, Expanded Granular Sludge Bed (EGSB) reactors, appeared as an alternative for implementing the anammox process. In this way, Lotti et al. [15] reported high nitrogen loading rates (NLRs) in an anammox EGSB reactor treating urban wastewater, even at 10 °C. In EGSB reactors, liquid V_{upS} are higher than 4 m h^{-1} to cause the granular sludge bed to expand [31]. For the implementation of the anammox process in EGSB such high V_{upS} are achieved by recycling part of the effluent, i.e. a liquid recirculation is used. Nevertheless, the need of a liquid recirculation is problematic for the real-scale implementation of the anammox process in the mainstream of urban WWTPs since too high recirculation flows would be needed and, consequently, operational costs would be unacceptable. By now, few studies have focused on the effect of V_{up} on the operation of anammox UASB (UAnSB) reactors and besides, to the best of the authors' knowledge, all have focused on operations with high-strength wastewaters [32,33].

Therefore, this study aimed to (i) implement the anammox process in an UASB reactor treating a low-strength synthetic influent achieving high nitrogen removal rates and high effluent quality, and (ii) study in depth the effect of the liquid V_{up} on the UAnSB reactor operation, specifically by following the granulation through the operation of the reactor.

2. Materials and methods

2.1. Reactor and experimental set-up description

The anammox process was carried out in a lab-scale UASB reactor with a working volume of 2 L including the gas-liquid-solid separator. The inner diameter of the column was 51 mm and the total-reactor-height to column-diameter ratio was 12.5. The detailed diagram of the reactor is present in Fig. 1. The pH was not controlled but measured offline and its value was 7.9 ± 0.2 during the whole operation, as the pH of the influent was set at 7.5 ± 0.2. Influent was devoid of oxygen since influent tank was periodically flushed with dinitrogen gas and additionally dinitrogen gas was introduced into the reactor headspace. DO concentration was measured in the bulk liquid of the reactor by means of a DO electrode (DO 60-50, Crison Instruments, Spain) and its value was always 0 mg L^{-1}. The temperature was measured and controlled by means of an electric heater (HBSI 0.8 m, HORST, Germany) connected to a temperature controller (BS-2400, Desin Instruments, Spain).

2.2. Reactor operation

The reactor operation was divided in four different periods, each one corresponding to a different NLR applied. The period I (days 0–50) corresponded to the start-up period when the NLR was gradually increased until a stable value was achieved. During period I, the temperature was controlled at 32 °C. Period II (days 50–200) corresponded to the stable operation at a fixed NLR. Period III (days 200–250) was a period of transition when NLR was gradually increased again, until achieving a stable value in Period IV (days 250–325). During periods II to IV, the temperature was controlled at 26 °C. NLR was changed by varying the inflow. Thus, changes in NLR led to changes in liquid V_{up} in the UAnSB reactor since the liquid V_{up} was only linked to inflow (no recirculation