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Control of nitratation in an oxygen-limited autotrophic nitrification/denitrification rotating biological contactor through disc immersion level variation

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HIGHLIGHTS

- Nitratation in an OLAND RBC could be controlled through the immersion level.
- 85–89% of the O_2 input was directly absorbed during the air exposure of the discs.
- Process control strategies solely based on DO level did not seem to be effective.

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ABSTRACT

With oxygen supply playing a crucial role in an oxygen-limited autotrophic nitrification/denitrification (OLAND) rotating biological contactor (RBC), its controlling factors were investigated in this study. Disc rotation speeds (1.8 and 3.6 rpm) showed no influence on the process performance of a lab-scale RBC, although abiotic experiments showed a significant effect on the oxygenation capacity. Estimations of the biological oxygen uptake rate revealed that 85–89% of the oxygen was absorbed by the microorganisms during the air exposure of the discs. Indeed, increasing the disc immersion (50 to 75–80%) could significantly suppress undesired nitratation, on the short and long term. The presented results demonstrated that nitratation could be controlled by the immersion level and revealed that oxygen control in an OLAND RBC should be predominantly based on the atmospheric exposure percentage of the discs.

1. Introduction

Oxygen-limited autotrophic nitrification/denitrification (OLAND) is a one-stage reactor technology removing ammonium from wastewaters with a low C/N ratio through a combination of partial nitritation and anammox (Kuai and Verstraete, 1998; Vlaeminck et al., 2012). In a biofilm-based configuration, OLAND relies on aerobic ammonium-oxidizing bacteria (AerAOB), which oxidize about half of the ammonium to nitrite in the outer, aerobic biofilm zones (partial nitritation), and anoxic ammonium-oxidizing, or anammox, bacteria (AnAOB), who subsequently convert nitrite and the residual ammonium to mainly nitrogen gas and some nitrate in the inner, anoxic biofilm zones. The optimal balance between AerAOB and AnAOB can however be disturbed by aerobic nitrite oxidizing bacteria (NOB), oxidizing nitrite to nitrate (nitratation) and thereby lowering the nitrogen removal efficiency. Oxygen supply thus plays a crucial role as sufficient oxygen is needed for nitritation but nitratation should be suppressed to allow sufficient anammox activity. Generally, a balanced OLAND system with maximum nitrogen removal efficiency can be obtained by sufficient dissolved oxygen (DO) limitation, stable hydraulic conditions and a thick biofilm (Vlaeminck et al., 2012). Moreover, NOB are more sensitive to free ammonia (FA) with inhibitory concentrations ranging between 0.08 and 0.82 mg NH_3–N L^{-1} compared with 8 and 120 mg NH_3–N L^{-1} for AerAOB (Anthonisen et al., 1976). For high-strength wastewaters NOB can thus also be suppressed by high FA concentrations.

A rotating biological contactor (RBC) is a biofilm-based reactor technology widely used for wastewater treatment and suitable for the OLAND process (Patwardhan, 2003; Pynaert et al., 2003; Vlaeminck et al., 2009). It typically consists of a series of discs mounted on a horizontal shaft, partially or completely submerged in the wastewater depending on the application. Rotation of the

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discs alternately exposes the biofilm to atmospheric oxygen and wastewater, providing aeration in a passive way. The RBC technology is popular due to its simple construction and operation, its robustness and its low operation costs. However, this cost-effective passive form of aeration complicates regulation of the oxygen budget, as it can only be indirectly controlled by immersion level and rotation speed of the discs. Generally, for a fixed immersion level of the discs, the oxygen transfer coefficient (K_La) increases with increasing rotational speed (Cortez et al., 2008). For a fixed rotation speed however, K_La is inversely proportional with the disc immersion. Aerobic processes typically use immersion of about 40% and, in most cases, higher organic removal rates are observed for increased rotation speeds (Israni et al., 2002; Najafpour et al., 2006). Elevated rotational speeds however lead to a higher power consumption and detachment of the biofilm resulting in lower degradation rates and lower effluent quality (Cortez et al., 2008).

In a RBC, oxygen may be transferred from the atmosphere by three mechanisms (Kim and Molof, 1982): (1) oxygen absorption at the liquid film on the disc's surface during the air-exposure cycle, (2) direct oxygen absorption by the microorganisms during the air exposure of the discs, and (3) direct oxygen transfer at the air-reactor liquid interface, with this diffusion being the result of the turbulence created by the rotating discs. Different empirical and mathematical models have been developed to estimate K_La in RBC (Friedman et al., 1979; Kubsad et al., 2004). Most of these models however, are based on physical studies, only accounting for two of the three possible oxygen transfer mechanisms (1 and 3), making it very difficult to model the oxygen transfer in more complex bioreactors. Indeed, some studies showed the importance of direct oxygen absorption by the microorganisms (mechanism 2) in a biotic RBC (Boumansour and Vasel, 1998; Paolini, 1986; Zeevalkink et al., 1979). Paolini (1986) namely observed a tenfold increase in the oxygen transfer capacity resulting from biological activity. However, there is a lack of information in literature the past decades about the importance of biological activity in the total oxygen transfer.

For the combined aerobic/anoxic OLAND process, where oxygen supply is a crucial process control parameter, the exact influences of disc rotation speed and immersion level on the performance in a RBC are not known and were therefore examined in this study. Combinations of two disc rotation speeds (1.8 and 3.6 rpm) and two disc immersion levels (50% and 75%) were tested on a short term (1 week) in a lab-scale RBC. Subsequently, different immersion levels were tested on a longer term (7–11 weeks) at 1.8 rpm, uncoupling the effects of increased immersion and free ammonia concentration. In parallel, oxygen transfer rates were determined in an identical abiotic setup to distinguish the different mechanisms (1 and 3 versus 2) in the total oxygen balance.

2. Methods

2.1. OLAND RBC

A mature OLAND RBC was used for the biotic experiments at 34 °C (Pynaert et al., 2003). The RBC consisted of 2 sets of 20 discs with a disc radius, disc thickness and disc interspace of 15, 0.5 and 1 cm, respectively. The reactor volume depended on the applied immersion level ranging from 42, 50 and 72 L for an immersion level of 39%, 50% and 80%, respectively. Before the start of the experiments, the OLAND RBC was operated at 50% immersion and a rotation speed of 1.8 rpm for several years. The synthetic influent consisted of $(NH_4)_2SO_4$ (1 g N L^{-1}), 7.5 g $NaHCO_3$ g^{-1} N and KH_2PO_4 (70 mg P L^{-1}) at a flow rate of 28 L d^{-1}, resulting in surface loading rate of 4614 mg N m^{-2} disc d^{-1}. The nitrogen loading was kept constant throughout the experiments, except for the last two periods in the long term experiment (as detailed below in section 2.2).

2.2. Effect of disc rotation speed and immersion level

In the short-term experiment, combinations of two disc rotation speeds (1.8 and 3.6 rpm) and two disc immersion levels (50% and 75%) were tested twice in the OLAND RBC, each for one week. In the long-term experiment (7–11 weeks), the effect of three disc immersion levels was tested twice (39%, 50% and 80%) at a disc rotation speed of 1.8 rpm. Furthermore, the effect of free ammonia (FA) inhibition was taken into account. Both at 50% and 80% immersion, the single effect of elevated FA concentrations was investigated. Moreover, the combined effect of FA and immersion level was also examined. The first increase in immersion from 50% to 80% was namely spontaneously accompanied with an increase in FA concentration. During the second transition from 50% to 80% immersion level, the nitrogen loading was decreased to prevent this FA increase and observe the single effect of immersion.

2.3. Physical oxygen transfer rate determination

In an identical abiotic RBC filled with tap water, the oxygen transfer coefficient (K_La) and the physical oxygen transfer rate (P-OTR) of each tested immersion speed combination was determined in batch experiments. The reactor liquid (tap water) was sparged with nitrogen gas to lower the DO level below 1 mg O_2 L^{-1}. Subsequently, the rotation was started, and the rise in DO level was monitored every 30 s. The K_La (d^{-1}) and P-OTR (mg O_2 L^{-1} d^{-1}) were calculated through the slope of the linear DO increase from about 0.5 to 2 mg O_2 L^{-1} over time. In the biotic OLAND RBC, these parameters were determined in a similar way following an interruption in the feeding of the reactor (leading to ammonium depletion).

2.4. Spatial and temporal patterns in microbial composition

Fluorescent *in situ* hybridization (FISH) was used to determine the NOB genus in the OLAND biomass, i.e. distinguish between *Nitrobacter* and *Nitrospira*, as a supporting analysis for the NOB target choice in the following qPCR analysis. OLAND biomass samples were examined by FISH as described by Vlaeminck et al. (2010).

Quantitative polymerase chain reaction (qPCR) was used to quantify the abundance of AerAOB, NOB and AnAOB over time and space in the RBC. During the long-term experiment, biomass samples were taken at both 50% and 80% immersion level from the first and the 20th disc. Biomass samples from both the peripheral part as the axial part of the disc were taken. DNA extraction and qPCR were performed according to De Clippeleir et al. (2012) targeting the functional *amoA* gene for AerAOB, and the 16S rRNA genes of the AnAOB (*Kuenenia* and *Brocadia*) and *Nitrospira* spp. All qPCR analyses were performed in triplicate and the standard series used for gene quantification showed a satisfactory C_T difference of 3.3 cycles between two dilutions, a slope value between −3.0 and −3.6 and a R^2 value $\geqslant 0.99$. In parallel, along the liquid plug flow path in the RBC, horizontal profile measurements of pH, ammonium, nitrite and nitrate in the bulk liquid were performed in triplicate at both 50% and 80% immersion level.

2.5. Chemical analyses

Ammonium (Nessler method) and volatile suspended solids (VSS) were determined according to standard methods (Greenberg et al., 1992). Nitrite and nitrate were determined on a 761 Compact ion chromatograph equipped with a conductivity detector