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Biological minimization of excess sludge in a membrane bioreactor: Effect of plant configuration on sludge production, nutrient removal efficiency and membrane fouling tendency

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ABSTRACT

Excess sludge minimization was studied in a MBR with pre-denitrification scheme. Sludge minimization, nitrogen removal performance and membrane fouling tendency were investigated in two configurations, characterized by a different position of the sludge retention reactor (SRR). In particular, the SRR was placed: i) in the return activated sludge line (Anaerobic Side-Stream Reactor – ASSR configuration) and ii) in the mainstream between the anoxic and aerobic reactor (Anaerobic Main-Stream Reactor – AMSR configuration). The achieved results demonstrated that the ASSR enabled a higher excess sludge reduction (74% *vs* 32%), while achieving lower biological nitrogen removal (BNR) (TN = 63% *vs* 78%) and membrane fouling tendency ($FR = 2.1 \cdot 10^{12}\ m^{-1}\ d^{-1}$ *vs* $4.0 \cdot 10^{11}\ m^{-1}\ d^{-1}$) than the AMSR. It was found that metabolism uncoupling, destruction of EPS and endogenous decay simultaneously occurred in the ASSR. Conversely, selective enrichment of bacteria population with low biomass yield was found the main mechanism affecting sludge minimization in the AMSR.

1. Introduction

Biological treatment by means of conventional activated sludge (CAS) has been widely employed to treat domestic and industrial wastewater worldwide. However, CAS plants require large volume to ensure high effluent quality and are very sensitive to fluctuations of organic and hydraulic loading rate (Capodici et al., 2016). Moreover, CAS plants imply high management costs related to the disposal of waste activated sludge (WAS). Indeed, it has been estimated that the costs of sludge disposal in a CAS wastewater treatment plants (WWTPs) takes up to 50–60% of the total operational costs (Campos et al., 2009; Torregrossa et al., 2012). The main alternatives for sludge disposal are represented by landfill, agricultural use and incineration, with average costs of \$30–100 per wet ton in Europe and \$30–70 per wet ton in Australia (Batstone et al., 2011). These amounts, when related to the dry solids, range approximately between 0.3 and 11 million tons of dry sludge per year (Yang et al., 2015). Therefore, the management and disposal of the waste activated sludge (WAS) have become one of the most debated challenges in wastewater biological treatments area.

In the last decade, membrane biological reactor (MBR) technology has been proposed as a suitable alternative to address the aforementioned issues because of its capability to perform higher effluent quality, smaller volumes and a lower amount of excess sludge production (Di Trapani et al., 2014). Nevertheless, there is an ideal tendency to achieve zero sludge waste that has pushed the research to further improvements toward this perspective.

Several promising methods for sludge minimization in MBRs were promoted in the past. Among these, the use of advanced oxidation processes that aims to destroy biomass (Wang et al., 2015), chemical addition to disrupt the metabolic processes (Fang et al., 2015) and the sludge cycling in alternating redox conditions by applying the oxic-anaerobic-settling (OSA) process (Semblante et al., 2014) have been widely examined. However, these alternatives are expensive (Foladori et al., 2010) and/or introduce into the water some undesired products (Mahmood and Elliott, 2006). Among the aforementioned solutions, the OSA process was suggested as one of the most potentially cost-effective and low impact alternative (Foladori et al., 2010; Semblante et al., 2016a). This process involves the modification of a CAS plant by placing a sludge retention reactor (SRR) in the return activated sludge (RAS) loop, thereby implementing the so called "anaerobic side-stream reactor (ASSR) configuration" (Velho et al., 2016). The anaerobic reactor allows the RAS to be degraded in the external reactor that has low

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DO and low substrate concentration, before it is returned to the aerobic reactor. The sludge hydrolysed in the anaerobic tank is returned to the activated sludge reactors to complete its oxidation. The alternation between conditions that are deficient (fasting - anaerobic reactor) and rich (feasting - aerobic reactor) in oxygen and substrate results in net excess sludge reduction (Semblante et al., 2016b). Several mechanisms contribute to sludge minimization, *inter alia* endogenous decay, extracellular polymeric substances (EPS) destruction, energy uncoupling, bacteria predation, etc. (Semblante et al., 2014). Literature findings suggest that those various mechanisms might simultaneously occur, thereby limiting a thorough understanding of the mechanism behind sludge minimization (Foladori et al., 2010; Semblante et al., 2014; Valentino et al., 2015). This approach led researchers to contradictory results about its impact on the nutrients removal performance and sludge physical properties (Coma et al., 2013). Therefore, further researches devoted to process optimization are still needed. Indeed, despite the OSA process coupled with MBR seems a promising technique for sludge minimization, only few studies were reported in the technical literature (Wang et al., 2013). Moreover, to authors' knowledge, except the ASSR, no further configurations regarding the placement of the anaerobic reactor in a MBR plant configuration were examined.

In this light, the aim of the present paper was to evaluate the minimization of excess sludge by the placement of an SRR in a MBR pilot plant with pre-denitrification scheme. In particular, sludge minimization, nitrogen removal performance and membrane fouling tendency were examined in two different configurations:

i) SRR in the return activated sludge line (Anaerobic Side-Stream Reactor – ASSR configuration);
ii) SRR in the mainstream between the anoxic and the aerobic reactor (Anaerobic Main-Stream Reactor – AMSR configuration).

2. Materials and methods

2.1. Pilot plant configuration

As aforementioned, the feasibility to implement an anaerobic SRR in a submerged MBR (sMBR) with a pre-denitrification scheme was examined in this study. Two plant configurations were studied, involving a different placement of the SRR in the pre-denitrification MBR layout. Fig. 1 illustrates the original MBR layout (Fig. 1a) as well as the two investigated alternatives, implementing the SRR in the side stream (Fig. 1b) or in the mainstream (Fig. 1c).

The original MBR layout (Fig. 1 a) was realized according to a pre-denitrification scheme. It consisted of one anoxic (18 L) and one aerobic tank (24 L). The MBR plant was fed in continuous mode with a flow rate of 2.3 $L\,h^{-1}$. The mixed liquor was pumped to the anoxic tank via an internal recycling characterized by a flow rate equal to 11.5 $L\,h^{-1}$ (RAS). The solid-liquid separation phase was achieved by an ultrafiltration hollow-fiber membrane module (PURON® Single bundle Demo, nominal pore size 0.03 μm, membrane area 0.47 m^2) placed within the aerobic tank in a submerged configuration. The membrane flux was maintained to approximately 4.9 $L\,m^{-2}\,h^{-1}$. The filtration cycle had a duration equal to 6 min, divided into 5 min of permeate extraction and 1 min of backwashing. The membrane backwashing was carried out by pumping a volume of permeate back through the membrane fibers from the Clean in Place (CIP) tank.

In the configuration depicted in Fig. 1b, the RAS line from the aerobic to the anoxic tank was pumped first into an SRR (13.8 L volume) with a flow rate equal to 2.3 $L\,h^{-1}$ and then recycled to the anoxic reactor. As above discussed, this configuration was named anaerobic side-stream reactor (ASSR).

In the configuration depicted in Fig. 1c, the SRR was placed in the main stream, between the anoxic and the aerobic tank. This configuration was named anaerobic main-stream reactor (AMSR), as previously mentioned. In both configurations, the interchange rate (the rate of solids passed through the SRR) was 100% and the hydraulic retention time (HRT) in the SRR was 6 h, equal to the 25% of the entire plant HRT. The anoxic and the SRR were continuously mixed by a mechanical stirrer. In the aerobic/membrane reactor, the oxygen was supplied by an air blower connected to a fine bubble diffuser placed at the bottom of the reactor. Furthermore, the same air blower supplied air to the membrane for fibers scouring, in order to mitigate the fouling extent.

2.2. Experimental campaign

The MBR was monitored for 153 days. The experimental campaign was divided into three periods, named MBR (I), MBR + ASSR (II) and MBR + AMSR (III), during which the MBR plant was operated according to the configurations above described. Specifically, the MBR operated with the conventional pre-denitrification scheme for 18 days, until steady conditions in terms of nutrient removal performance and excess sludge production were achieved. During this period, the excess sludge production was evaluated in terms of observed heterotrophic growth yield (Y_{obs}) and this latter was assumed as the reference value to evaluate the impact of the other plant configurations in terms of sludge minimization efficiency. Hereafter, the MBR operated in ASSR configuration for 45 days until steady-state excess sludge production was achieved. Lastly, the MBR operated in AMSR configuration for 90 days until the end of the experiment.

The MBR was seeded with activated sludge collected from a municipal WWTP with a conventional activated sludge scheme (inoculum TSS equal to 3.63 $gTSS\,L^{-1}$). The sludge retention time (SRT) was not controlled and no dedicated wasting operations of sludge were carried out, excepting the samples withdrawn to perform chemical-physical analyses. Approximately 100 mL of mixed liquor were withdrawn daily, thereby resulting in a SRT more than 500 days. Therefore, it can be assumed that the pilot plant was operated with a complete sludge retention strategy. The achievement of steady state conditions in each phase was evaluated basing on the biological performance, kinetic parameters and sludge production.

The MBR was fed with synthetic wastewater during the entire experiment. The synthetic wastewater composition was (in 100 L of tap water): 4.5 g of peptone, 15 g of sodium acetate (CH_3COONa), 4 g of urea (CH_4N_2O), 14.5 g of ammonium chloride (NH_4Cl) and 6 g of dipotassium phosphate (K_2HPO_4). Table 1 summarizes the average features of the influent wastewater as well as the main operating conditions throughout experiments.

2.3. Analytical methods

All the chemical-physical analyses including total and volatile suspended solid (TSS, VSS) concentrations, total chemical oxygen demand (TCOD), total nitrogen (TN), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), nitrite nitrogen (NO_2-N) and total phosphorous (TP) were performed according to standard methods (Apha, 2005). TSS and VSS were measured in the mixed liquor of all the reactors. The COD, TN, NH_4-N, NO_3-N, NO_2-N were measured at the inlet and at the outlet of each reactor as well as in the permeate. Specifically, the TCOD was measured in the supernatant of mixed liquor samples (after centrifugation at 4000 rpm for 30 min). Dissolved oxygen (DO) concentration, oxidation-reduction potential (ORP) and pH were measured in all the reactors by means of specific probes (WTW 3310).

2.4. Evaluation of biomass growth and heterotrophic kinetics parameters

The effectiveness of the implemented process configurations in terms of sludge minimization was evaluated through the Y_{obs} monitoring.

The Y_{obs} values were calculated through mass balances between sludge withdrawn and sludge production, dividing by the cumulated