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Research article

Integrated fixed-film activated sludge membrane bioreactors versus membrane bioreactors for nutrient removal: A comprehensive comparison

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ABSTRACT

This research elucidates the pollutants (nutrients and carbon) removal performance and nitrous oxide (N_2O) emissions of two pilot plants. Specifically, a University of Cape Town (UCT) Membrane Bioreactor (MBR) plant and an Integrated Fixed Film Activated Sludge (IFAS)-UCT-MBR plant were investigated. The plants were fed with real wastewater augmented with acetate and glycerol in order to control the influent carbon nitrogen ratio (C/N). The short-term effect of the inlet C/N ratio variation (C/N = 5 mgCOD/mgN and C/N = 10 mgCOD/mgN) on the behaviour of both plants was investigated. The results showed that the IFAS-UCT-MBR configuration provided the best performance in terms of pollutants removal at the two investigated C/N ratios. Furthermore, the lowest N_2O emission (with respect to the influent nitrogen) was observed in the IFAS-UCT-MBR configuration, thus suggesting a potential beneficial effect of the biofilm in the emission reduction. However, the membrane of the IFAS-UCT-MBR showed a greater fouling tendency compared to the UCT-MBR configuration. This result, likely related to the biofilm detached from carriers, could seriously affect the indirect GreenHouse Gas emissions due to the increase of the energy requirement for permeate extraction with the increase of membrane fouling.

1. Introduction

It is well known that nutrients conveyed with wastewater (either raw or treated), like nitrogen (N) and phosphorus (P) compounds, might produce negative effects on the receiving water bodies, affecting their quality level. High concentration of nutrients can promote eutrophication as well as direct toxicity for the aquatic organisms (Wang et al., 2006). Therefore, tertiary treatment for N and P removal from wastewater becomes a prominent requirement especially when discharging into "sensitive areas". In the last years, biological nutrient removal (BNR) processes have been thoroughly investigated. BNR processes have several advantages compared to the chemical processes (for P-removal), in terms of chemical consumption, energy requirements and production of chemical sludge.

Traditionally, BNR is carried out by combining anaerobic, anoxic and aerobic conditions within separate reactors (Naessens et al., 2012). Nitrogen removal is usually achieved by the joint activity of ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB) for nitrification. Heterotrophic organisms generally handle denitrification. In contrast, biological phosphorus removal relies on the ability of phosphorus accumulating organisms (PAOs) to accumulate P as intracellular polyphosphate under the alternation of anaerobic/aerobic condition. Conventional activated sludge (CAS) processes have been proven to be effective for the removal of organic carbon and nutrients. However, an important drawback of CAS systems is the required significant volumes, making CAS solution expensive. Moreover, the overall efficiency strongly depends on the performance of the final settler for solid-liquid separation, which may suffer of many separation problems (Wanner, 2002).

Therefore, new advanced technologies were explored by the scientific community over the last years. Among the innovative technologies, the combination of membrane bioreactor (MBR) and moving bed biofilm reactor (MBBR) introduced two different ways for the improvement of the system performance: (a) the use of membrane for the solid-

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liquid separation and (b) the use of suspended carriers for biofilm growth inside the bioreactor (Leiknes and Ødegaard, 2007; Leyva-Díaz et al., 2016a; Yang et al., 2014). When operated in a hybrid configuration, thus enhancing the simultaneous growth of activated sludge and biofilm, these systems are usually referred to as MBBR-based Integrated Fixed Film Activated Sludge (IFAS) membrane bioreactors (IFAS-MBR) (Mannina et al., 2017b).

There are several advantages of using IFAS compared to CAS (Ødegaard et al., 2014; Ødegaard, 2017). The main benefit of IFAS is that nitrification can be obtained at less than half of the (Mixed Liquor Sludge Retention Time) SRT_{MLSS} than that required in CAS systems. Moreover, at low SRT_{MLSS} more carbon will be available for denitrification through hydrolysis of the MLSS. Several studies have shown that the specific denitrification rate in IFAS systems is around twice that of CAS systems (Onnis-Hayden et al., 2007; Rusten et al., 2003). Hence, the IFAS-MBR systems require a smaller volume for nitrification and denitrification than conventional MBR systems. The combination of IFAS and MBR has several advantages compared to the CAS or MBR systems.

Feng et al. (2016) highlighted sludge yield reduction, denitrification increase and decrease of membrane fouling in a system combining MBBR and MBR. Leyva-Díaz and co-workers (Leyva-Díaz et al., 2013) observed higher nitrification-denitrification in a IFAS-MBR system compared to a traditional MBR; they underlined the potential occurrence of the simultaneous nitrification-denitrification within the biofilm. IFAS-MBR systems are relatively new; therefore, further experiments are required in order of improving knowledge. The influent carbon-to-nitrogen (C/N) ratio may affect the performance of the system, referring in particular to the nitrification-denitrification processes (Fu et al., 2009). This aspect is of paramount importance concerning greenhouse gas (GHG) emission, referring in particular to nitrous oxide (N_2O) since it is mainly produced during nitrogen removal processes (Kampschreur et al., 2009). Nevertheless, only few studies have been carried out with this regard in MBR-biofilm systems so far (Mannina et al., 2017a; Todt and Dörsch, 2016).

The goal of the present paper is to compare the performance of two different MBR pilot plants realized according to the University of Cape Town (UCT) layout (namely, IFAS-UCT-MBT and UCT-MBR).

In particular, this study analyses the short-term effect of the influent C/N variation (Phase I – C/N = 5; Phase II – C/N = 10) on organic carbon and nutrient removal, biomass respiratory activity and membrane fouling propensity. Moreover, the paper aims at assessing the overall N_2O emissions from both UCT-MBR and IFAS-UCT-MBR systems, evaluating the C/N variation and elucidating the potential beneficial role played by the biofilm presence. The novelty aspects of the present study are represented by a focus on N_2O production/emission as well as sludge dewaterability features in MBR systems with and without the biofilm presence, scarcely investigated in previous studies.

2. Materials and methods

2.1. The pilot plant

Two pilot plants were analysed: a UCT-MBR and a IFAS-UCT-MBR (Fig. 1). Both pilot plants have the same layout according to the UCT-MBR scheme. More precisely, three reactors in series (anaerobic, anoxic and aerobic) were followed by a membrane reactor (MBR). Inside the membrane reactor an ultrafiltration hollow fiber membrane module (Koch Puron® 3 bundle) (pore size of 0.03 μm and membrane net area of 1.4 m^2) was located. For both pilot plants the reactors have the same volume. The key difference between the two pilot plants is the presence, only for the IFAS-UCT-MBR plant, of suspended plastic carriers (Amitech®, density = 0.95 g cm^{-3}; specific surface = 500 $m^2 m^{-3}$). These carriers were inserted only inside the aerobic (filling ratio of 40%) and anoxic (filling ratio of 15%) tanks. The presence of carriers makes quite different the behaviour of biological processes inside the aerobic and anoxic tanks of the IFAS-UCT-MBR plant compared to the UCT-MBR plant due to the combined effect of suspend biomass and biofilm.

Permeate flow rate was equal to 20 L h^{-1} (Q_{IN}). The mixed liquor (Q_{R1}, 20 L h^{-1}) from the anoxic to the anaerobic tank was continuously recycled. Furthermore, a 100 L h^{-1} flow rate (Q_{R2}) of mixed liquor was pumped from the aerobic to the MBR tank. The membrane was periodically backwashed (every 10 min for a period of 1 min) by pumping, from the Clean In Place (CIP) tank a volume of permeate back through the membrane module (Q_{BW}). The net permeate flow rate discharged was equal to 20 L h^{-1} (Q_{OUT}). Activated sludge was also continuously recycled from the MBR to the anoxic tank through the oxygen depletion reactor (ODR) tank sludge (80 L h^{-1}, Q_{RAS}). The ODR has the function of reducing the amount of dissolved oxygen recycled from the MBR to the anoxic tank. The covers on the anaerobic, anoxic, aerobic and MBR reactors allowed the collection of the off-gas produced from each reactor.

Municipal wastewater was treated within both pilot plants. However, the inlet C/N ratio was controlled by adding a synthetic mixture to the municipal wastewater (composed by sodium acetate, glycerol, dipotassium hydrogen phosphate, and ammonium chloride).

For both configurations, the experimental campaign was divided into two phases: i. the influent C/N was equal to 5 mgCOD/mgN; ii. the influent C/N was equal to 10 mgCOD/mgN.

The average inlet COD concentration for the UCT-MBR was equal to 411 mg L^{-1} (58% coming from synthetic wastewater) and 502 mg L^{-1} (78% coming from synthetic wastewater) for the experimental phase at C/N equal to 5 and 10 mgCOD/mgN, respectively (Mannina et al., 2017b). The average inlet total nitrogen (TN) concentration for the UCT-MBR was equal to 99 mg L^{-1} (52% coming from synthetic wastewater) and 52.6 mg L^{-1} for the experimental phase at C/N equal to 5 and 10 mgCOD/mgN, respectively. The ammonium chloride has been added only for the UCT-MBR plant during the experimental campaign at C/N equal to 5 mgCOD/mgN (Mannina et al., 2017b). While, the average inlet COD concentration for the IFAS-UCT-MBR was equal to 543 mg L^{-1} (56% coming from synthetic wastewater) and 864 mg L^{-1} (73% coming from synthetic wastewater) for the experimental phase at C/N equal to 5 and 10 mgCOD/mgN, respectively (Mannina et al., 2017c). The average inlet total nitrogen (TN) concentration for the IFAS-UCT-MBR was equal to 92 mg L^{-1} and 80 mg L^{-1} for the experimental phase at C/N equal to 5 and 10 mgCOD/mgN, respectively (Mannina et al., 2017c).

The UCT-MBR plant was operated at a mixed liquor sludge retention time (SRT_{MLSS}) of 50 days at the influent C/N = 5 mgCOD/mgN and 40 days at the influent C/N = 10 mgCOD/mgN. The IFAS-UCT-MBR plant was operated at SRT_{MLSS} of 65 days at the influent C/N = 5 mgCOD/mgN and 40 days at the influent C/N = 10 mgCOD/mgN. It should be noted that these SRT's are much higher than what would normally be used in practice – especially for the IFAS-UCT- MBR case and the potential for smaller foot-print by the use of IFAS-UCT-MBR as compared to MBR could not be analysed in this investigation.

2.2. Analytical methods

During the experimental campaign, samples were collected two times per week from the influent, effluent and intermediate sections of both plants. The samples were analysed using Standard Methods (APHA, 2012) for: chemical oxygen demand (COD), biochemical oxygen demand (BOD), total nitrogen (TN), ammonium nitrogen (NH_4–N), nitrate nitrogen (NO_3–N), nitrite nitrogen (NO_2–N), orthophosphate (PO_4–P).

Furthermore, the nitrification (η_{nit}), denitrification (η_{denit}) and total nitrogen (η_{Ntotal}) removal efficiencies were evaluated according to (Mannina et al., 2017c). In order to discriminate between the COD removal due to the biological processes and the physical effect of membrane, the following removal efficiencies were evaluated according to (Mannina et al., 2017c): biological removal efficiency (η_{BIO});