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Carbon and nutrient biological removal in a University of Cape Town membrane bioreactor: Analysis of a pilot plant operated under two different C/N ratios

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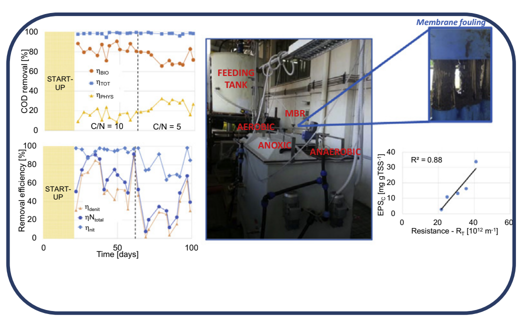
HIGHLIGHTS

- A UCT-MBR pilot plant subjected to a C/N variation was investigated.
- The biological performances were significantly affected by the C/N decrease.
- Competition between PAOs and denitrifying species decreased P removal dramatically.
- Respirometry showed that nitrification was significantly affected by C/N decrease.
- A reduction of membrane filtration performance due to the increase of EPS took place.

GRAPHICAL ABSTRACT



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ABSTRACT

The effect of the carbon-to-nitrogen (C/N) ratio variation in a University of Cape Town Membrane bioreactor (UCT-MBR) was investigated. The experimental campaign was divided into two phases, each characterized by a different C/N ratio (namely, 10 and 5, Phase I and Phase II, respectively). The UCT-MBR pilot plant was analysed in terms of carbon and nutrients removal, biomass respiratory activity, activated sludge features and membrane fouling. The results highlighted that the nutrients removal was significantly affected by the decrease of the C/N ratio during the Phase II. The biological carbon removal was also affected by the low C/N value during the Phase II. Indeed, the average biological COD removal efficiency was equal to 72.9% during the Phase II, while the average value was 82.8% in the Phase I. The respirometric batch test suggested that both heterotrophic and autotrophic species were severely affected by the lower C/N ratio in the Phase II. Moreover, a decrease of the membrane filtration properties was observed during the Phase II, mainly due to the worsening of the activated sludge features, which enhanced the increase of SMP production.

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1. Introduction

Nitrogen (N) and phosphorus (P) play a crucial role in water eutrophication thus requiring their removal from wastewater especially when discharged in sensitive areas [1]. Biological nutrient removal (BNR) from domestic wastewater has been extensively investigated and developed in the last years and it is usually based on anaerobic, anoxic and aerobic reactors linked in-series (*among others*, Wanner et al. [2]; Cosenza et al. [3]; Lu et al. [4]). In BNR processes, N and P removal is accomplished, respectively, by heterotrophic denitrifying bacteria and polyphosphate-accumulating organisms (PAOs) which require carbon source [5]. In particular,

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the biological phosphorous removal is commonly conducted by exploiting the ability of PAOs to accumulate P and to store it as intracellular polyphosphate (poly-P) under alternating anaerobic/aerobic conditions [1]. Therefore, in BNR systems the sufficient amount of a carbon source is crucial for the proper removal of nitrogen and phosphorous [6]. However, when treating wastewater characterized by low carbon-to-nitrogen (C/N) ratio the rapid enrichment of PAOs could not be achieved and another group of microorganisms usually known as glycogen accumulating organisms (GAOs) might compete with PAOs for the available organic substrate without contributing to P removal [7]. Furthermore, at low C/N the NO_3-N in the return sludge (from anoxic, or aerobic, tank to the anaerobic one) can inhibit the phosphorus release in anaerobic zone where denitrifiers compete with PAOs for carbon source, consequently the phosphorus release does not occur until denitrification is completed [8].

Therefore, the C/N ratio represents a key parameter for nutrient removal from wastewater. Indeed, in terms of nitrogen removal C/N ratio might directly affect the activity of functional microorganism species, including autotrophic populations, such as ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB), as well as heterotrophic denitrifying bacterial species [9]. Indeed, the decrease of the C/N ratio mainly related to increase of ammonia loading rates might significantly reduce the activity of specific nitrifying populations and can severely hamper the nitrification and/or nitrogen removal [10]. Among others, Choi et al. [11] investigated the effects of C/N ratios on an intermittently aerated membrane bioreactor (MBR) system. Choi and co-workers found that a C/N ratio over 7 is required for nitrogen removal; conversely, authors found that a C/N ratio of 4.5 promotes a decrease of nitrogen removal capacity. In terms of phosphors removal, studies on the influence of C/N ratio have been mainly performed on conventional activated sludge (CAS) systems: CAS combined with biological aerated filter (BAF) [12] and sequential batch reactors (SBR) [13]. Literature shows that C/N ratio has a significant effect on P removal in CAS systems or SBR. Specifically, at moderate C/N ratio (e.g., C/N = 6) P can be released inside the settling tank due to the occurrence of anaerobic condition and the availability of soluble carbon sources [12].

Recently, the integration of BNR process with membrane bioreactor (MBR) as an efficient combined process has been proposed for the wastewater treatment to treat the quality of the effluent, including such BNR processes as University of Cape Town (UCT) process, anoxic/oxic (A/O) process and anaerobic/anoxic/oxic (A^2O) process [14]. Indeed, MBRs have attracted considerable interest due to various advantages compared to conventional process that originate from the use of a membrane for solid–liquid separation [9]. In particular, MBRs generally feature high quality effluent, small footprint and low sludge production rates compared to CAS systems [15]. In terms of P removal, MBRs preserve from the release of P inside the settling tank in case of anaerobic conditions and carbon availability. Moreover, previous investigations highlighted that incorporating membranes into BNR activated sludge systems could have a profound difference not only in the design of the BNR system but also in the operation for the whole wastewater treatment plant (WWTP) [16].

However, few studies can be found in the technical literature on the role that the C/N variation play on the performance of a BNR system including MBR, referring in particular to the removal pollutant (i.e., carbon and nutrients) efficiencies, biomass biokinetic behaviours and membrane fouling. Recently, Xiang et al. [17] investigated a full scale modified A_2O–MBR plant combined with the step feed strategy and operated at low C/N ratio (3.8). Xiang and co-workers found that at low C/N the addition of external carbon source was required to improve TN and TP removal efficiencies. However, as authors are aware, no studies have yet been performed comparing the behaviour of an MBR in terms of COD removal and BNR for different values of influent C/N. Furthermore, although there are several studies carried out separately on membrane processes and BNR in conventional activated sludge processes, the combination of membrane and BNR processes needs further studies to optimize the full scale processes to be used.

Bearing in mind these considerations, the aim of the paper is to explore the effect of a C/N ratio variation on a BNR process integrated with a membrane for the solid–liquid separation phase. In detail, the objective was to assess the impact of C/N variation in terms of carbon, nitrogen and phosphorous removal, nitrification ability, biomass respiratory activity and membrane fouling. To accomplish such goal, an UCT-MBR pilot plant was built-up and fed with a mixture of real domestic and synthetic wastewater. The UCT-MBR pilot plant was started-up with a C/N ratio equal to 10 (Phase I) that was decreased to 5 (Phase II) by increasing the influent ammonia loading rate.

2. Material and methods

2.1. Pilot plant and sampling campaign

An UCT-MBR pilot plant was built at the Laboratory of Sanitary and Environmental Engineering of Palermo University (Fig. 1). The pilot plant consisted of an anaerobic (volume 62 L), an anoxic (volume 102 L) and an aerobic (volume 211 L) tanks according to the UCT scheme [18]. The solid–liquid separation phase was carried out by means of an ultrafiltration hollow fibre membrane (PURON®). The membrane module was located inside an aerated tank (MBR tank) (36 L). An oxygen depletion reactor (ODR) allowed the oxygen stripping in the mixed liquor recycled from the MBR tank to the anoxic one (Q_{RAS}). The membrane was periodically backwashed (every 9 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. The extraction flow rate was set equal to $20\ L\ h^{-1}$ (Q_{in}). During the pilot plant operations, a $20\ L\ h^{-1}$ flow rate (Q_{R1}) was continuously recycled from the anoxic to the anaerobic tank. Furthermore, a $100\ L\ h^{-1}$ flow rate (Q_{R2}) of mixed liquor was pumped from the aerobic to the MBR tank. A net permeate flow rate of $20\ L\ h^{-1}$ was extracted (Q_{OUT}) through the membrane module. Therefore, the recycled activated sludge (Q_{RAS}) from the MBR to the anoxic tank through the ODR tank was equal to $80\ L\ h^{-1}$.

The pilot plant was fed with municipal wastewater mixed with a synthetic wastewater characterized by Sodium Acetate (CH_3COONa), glycerol ($C_3H_8O_3$), dipotassium hydrogen phosphate (K_2HPO_4) and ammonium chloride (NH_4Cl). The synthetic wastewater was added in order to control the C/N ratio fed to the pilot plant. The UCT-MBR pilot plant was started up with sludge inoculum, withdrawn from the WWTP of Palermo, to obtain an initial total suspended solid (TSS) concentration of $3500\ mg\ L^{-1}$. After a 20 days start-up phase, the experimental campaign was divided in two phases each characterized by a different C/N value: (i) Phase I, with a C/N = 10 (duration: 41 days); (ii) Phase II, C/N = 5 (duration: 39 days). During both periods, the UCT-MBR pilot plant was operated with periodical sludge withdrawals with the aim to obtain an average weighted TSS concentration of $5\ g\ L^{-1}$. In Table 1 the main influent and operational features and Standard Deviations (SD) of both experimental phases are reported.

During pilot plant operations, the influent wastewater, the mixed liquor inside the anaerobic, anoxic, aerobic and MBR tank and the effluent permeate have been sampled and analysed for TSS, volatile suspended solids (VSS), total chemical oxygen demand (COD_{TOT}), supernatant COD (COD_{SUP}), ammonium nitrogen

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