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Fouling analysis of a tertiary submerged membrane bioreactor operated in dead-end mode at high-fluxes

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Fouling deposition, consolidation and reversibility were assessed in a tertiary submerged membrane bioreactor. The unit was operated in dead-end mode (i.e. without air scouring during the filtration) and with an alternative physical cleaning strategy based on *TMP* set-point initiation. Several operating parameters such as filtration and backwashing fluxes, backwash duration and the aid of air scouring during backwashing were studied. The aim of the work was to optimise membrane productivity, specific aeration demand and operative time between chemical cleanings. The membrane bioreactor was operated for over 4 months with complete sludge retention, achieving a high treatment performance with moderate suspended solids concentration (MLSS = 4–8 g/L). Flux-step trials pointed to the important role of the compression process and backwashing conditions in membrane fouling reversibility. During long-term tests, while reversible fouling was described by the compressible cake build-up model, residual fouling was modelled by a non-linear expression, assuming that fouling gradually reduces the available membrane area. Based on this approach, residual fouling consistently decreased with the backwashing flux applied. Analysis of the relative contribution of the different fouling layers revealed that the fraction formed by suspended solids was the main contributor. According to the residual fouling model, optimal membrane production can be established at a filtration flux of 40 L/h m^2 and a backwashing flux of 27.5 L/h m^2, due to the low specific energy demand, low membrane area requirement and reasonable operative time (t_{op}) between chemical cleanings.

1. Introduction

Growing worldwide water supply demands and the protection of water bodies have both increased the interest in wastewater reclamation. Legislation affecting reclaimed wastewater reuse is very demanding regarding quality and health safety, which has required the application of advanced technology. Among such techniques, the use of membranes emerges as a highly efficient system to obtain high quality recycled water. In fact, low-pressure membrane filtration (microfiltration or ultrafiltration) of biologically degraded secondary effluents has been widely applied for upgrading conventional wastewater treatment plants [1]. However, in the case of old plants with poor performance of secondary clarifiers which often leads to sludge bulking, the relatively high concentration of suspended solids in secondary effluents can compromise the economic feasibility of the membrane filtration processes [2]. In this scenario, a tertiary submerged membrane bioreactor (MBR) appears to be an attractive option for advanced treatment of secondary effluent. As described in previous research [3], the tertiary MBR has demonstrated its capability of achieving high organic carbon removal and complete nitrification, regardless of high variability in the feedwater. As a consequence of the substrate-limited conditions, the microbial suspension generated in the bioreactor has suitable filtration properties (i.e. large flocs, presence of higher organisms and a low concentration of soluble microbial products). The growing interest in this technology is to be seen recently in the Aquapolo project (Sao Paulo, Brazil), the largest wastewater reuse project in the Southern Hemisphere, which includes a tertiary MBR in the treatment scheme [4].

As in all membrane processes, fouling is still the main drawback of MBRs, preventing wide application [5]. Fouling can be defined as the alteration in the membrane caused by specific physical and/or chemical interactions between the membrane and the components of the microbial suspension, which leads to membrane permeability loss. The rate and extent of fouling is typically a complex function of membrane properties, operating

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conditions and microbial suspension characteristics [6]. Microbial suspension is a heterogeneous system mainly composed of salts, organic substances, colloids, cells and microbial flocs. Several mechanisms have been proposed to explain this complex phenomenon, including pore clogging, adsorption of foulants, gel or cake formation, cake layer consolidation and osmotic pressure effects [7].

In order to maintain membrane permeability, strategies for fouling mitigation such as air scouring, physical cleaning techniques (i.e. relaxation and backwashing) and chemical cleaning have been incorporated into MBR designs [5]. Based on permeability recovery by physical means, membrane fouling can be classified into two main types. The first one is known as reversible fouling (caused by loose cake deposit and possibly by pore clogging) and refers to fouling which can be removed by physical means. The second type is residual fouling, which is related to foulant adsorption, gel formation, and possibly consolidated cake deposition, and can only be removed by chemical cleaning [8].

In spite of the significant impact of fouling on membrane productivity, module lifespan and energy requirements [8], strategies for fouling control are usually based on predetermined values of the operating parameters (air scouring flow-rate and frequency, and filtration/physical cleaning sequences), which lead to an under-optimised system [5]. Air scouring has been extensively proven to be an efficient means to limit foulant deposition due to the enhancement of foulant back-transport, the shear stress induced at the membrane surface and the lateral fibre movement (in hollow fibre modules) [10]. Because of its impact on energy demand, several strategies have been implemented, mainly focused on adjusting flow rate and/or frequency of coarse air bubbles [11]. Typically, it takes a value of 12–13 Nm^3/m^3, expressed as specific aeration demand per permeate volume unit (SAD_p), for full-scale facilities [12]. Also, pulse scouring with large bubbles was recently introduced as a means to increase scouring efficiency [13]. However, air scouring is still considered the greatest energy consumer in these processes, often exceeding 50% of total energy consumption [12]. Therefore, the priority is to explore operation modes with lower energy consumption. An alternative approach could be to operate in dead-end filtration mode (i.e. without air scouring). In that case, due to absence of shear forces, foulants back-transport is significantly decreased (by ceasing the transport mechanisms of lateral migration and shear induced diffusion) and consequently, net foulants transport towards the membrane is increased. Hence, to maintain a sustainable process operation at reasonable fouling rate, filtration flux should be decreased and frequent physical cleanings should be applied. This disadvantage must be compensated by alternative physical cleaning strategies, as it is discussed below.

Conventional physical cleaning techniques include backwashing (i.e. permeate is used to flush backwards) or relaxation (ceasing filtration whilst continuing air scouring). For both methods, the key parameters generally identified are frequency and duration [6]. Additionally, another parameter influencing cleaning efficiency of backwashing is its intensity, which typically ranges between 1 and 3 times the filtration flux [14]. According to several studies of backwashing, a higher cleaning efficiency is observed with increasing backwashing flux, frequency and duration [15]. Nevertheless, given the impact of these parameters on process productivity, optimisation of backwashing conditions is still needed [16]. In this direction, a recent review study has highlighted the variety of operating trends. This is attributable to the fact that selection of appropriate cleaning protocols for a sustainable operation depends on other process variables (i.e. filtration flux, air scouring, temperature, etc.) and suspension filterability [14]. As a consequence, pre-set values of these parameters are often selected in full-scale plants [15], where the operating trend is to perform a very frequent backwashing cycle (once every 3.3–8.3 min of filtration) [17]. In recent years, several feedback control systems have been developed for physical cleaning optimisation [11]. Among them, a system has been successfully implemented for physical cleaning initiation through transmembrane pressure (*TMP*) monitoring. This automatically adjusts the backwashing frequency to a preselected *TMP* set-point, which results in a significant increase in process productivity [18]. Additionally, by selecting a moderate *TMP* set-point (30–40 kPa), effective fouling control has been achieved, allowing operation under less conservative conditions (supra-critical fluxes) [3,19].

As previously stated, dead-end operation could be an attractive option due to its lower energy demand. In fact, it has been widely used in direct ultrafiltration of secondary effluents [20]. Nevertheless, the higher quantity of suspended solids in the MBR (several orders of magnitude higher than that of a secondary effluent) significantly increases the fouling rate and limits its applicability. However, fouling rate not only depends on cake solids concentration (ω) but also on the specific cake resistance (α), which is determined by the geometrical properties of the deposit (porosity, particle diameter, etc.) [21]. Recent studies have reported significantly lower values of α for cake layers formed by microbial flocs (10^{12}–10^{13} m/kg) than that (10^{14} m/kg) obtained for gel layers mainly composed of soluble microbial products (SMP), which are considered the most important foulant in secondary effluents [22]. Therefore, highly porous aggregates with low resistances are expected to form during the filtration without air scouring of a microbial suspension. In addition, the cake layer may act as a secondary membrane that prevents residual fouling caused by pore blocking or adsorption due to SMP [23]. Another issue to be considered is the deposit reversibility, since it is known that increasing the fouling load on the membrane reduces the removal efficiency. In general, it is expected that high filtration *TMP* results in a more compact cake layer, harder to remove by physical cleaning [24]. Nevertheless, cake compressibility also depends on other factors including particle characteristics (morphology, size, etc.) and hydrodynamics of cake formation process. Accordingly, although physical cleaning strategy based on the *TMP* set-point seems to be a suitable approach to reduce residual fouling, the optimal value of TMP_{sp} is site specific. Therefore, for a given system, it is necessary an experimental evaluation of the effect of TMP_{sp} on fouling consolidation and reversibility.

The aim of this study was to investigate fouling deposition, its consolidation and reversibility in a tertiary submerged membrane bioreactor operating in dead-end mode (i.e. filtration without air scouring) during long-term trials. An alternative physical cleaning strategy based on *TMP* set-point initiation was applied. Several operating parameters such as filtration and backwashing fluxes, backwashing duration and the aid of air scouring during the backwashing were studied in order to optimise membrane productivity and the specific energy demand.

2. Material and methods

2.1. Feedwater

The pilot MBR was fed with effluent from a conventional activated sludge wastewater treatment plant whose average physico-chemical characteristics are given in Table 1. The conventional WWTP was originally designed for only carbon removal. Due to the short sludge ages and oxygen deficiency in the activated sludge process, frequent episodes of sludge de-flocculation or insufficient sedimentation usually appear, resulting in higher suspended solids and organic material concentration in the effluent.