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Effects of scale-up on a hybrid moving bed biofilm reactor – membrane bioreactor for treating urban wastewater

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HIGHLIGHTS

- Hybrid MBBR–MBR was reliable for COD removal (higher than 90.97 ± 2.55%).
- Hybrid MBBR presents a better kinetic behaviour and higher removal rate in pilot scale.
- Variations of organic loading and temperature are two effects of the scale up.
- The scale of working affects the sludge retention time and attached biomass.

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ABSTRACT

A hybrid moving bed biofilm reactor–membrane bioreactor (hybrid MBBR–MBR) system has been tested in this study at two scales to analyse the scale-up effect. Two municipal wastewater treatment plants were used, one at laboratory scale (hybrid MBBR–MBR_L) with a reactor working volume of 24 l and one at pilot scale (hybrid MBBR–MBR_P) with a reactor working volume of 358 l. Hybrid MBBR–MBR_L and hybrid MBBR–MBR_P showed that the hybrid MBBR–MBR systems used in this research were reliable for organic matter removal with COD removal percentages of 90.97 ± 2.55% and 95.56 ± 2.01% for hybrid MBBR–MBR_L and hybrid MBBR–MBR_P, respectively. In hybrid MBBR–MBR_L, the sludge retention time was higher but the biofilm density was lower due to the wall effect, so the two effects cancelled one another out and the COD removal efficiencies were found to be similar. The study identified the most influential variables and their effects on the process. Hybrid MBBR–MBR_L and hybrid MBBR–MBR_P were influenced by the attached and suspended biomass and temperature, while the influent loading rate only affected hybrid MBBR–MBR_P. On the whole, hybrid MBBR–MBR_P showed a better performance from the point of view of the kinetics of the heterotrophic biomass, with values of $Y_H = 0.6130$ mg VSS mg COD^{-1}, $\mu_{m,H} = 0.0146$ h^{-1}, $K_S = 9.8852$ mg O_2 L^{-1}, and $b_H = 0.0031$ h^{-1}.

1. Introduction

As a consequence of increasing urbanisation, industrial development, and changes in farming practices, which have caused a huge rise in the consumption of water resources as well as deterioration in their quality (Wang et al., 2006), advanced technologies regarding wastewater treatment are necessary to preserve water quality and to satisfy the limits imposed on the effluent from municipal wastewater treatment plants (WWTPs) by the Water Framework Directive (Chave, 2001). Biological processes allowing a complete wastewater treatment are required (Di Trapani et al., 2010a). Moreover, they could be improved by efficient physical separation technologies such as the use of membranes.

A membrane bioreactor (MBR) system constitutes an alternative solution for overloaded conventional WWTPs, replacing the settling tank with membrane filtration (Gunder and Krauth, 1998; Van der Roest et al., 2002). MBR is a compact system which makes it possible to improve the quality of the effluent by reducing the number of pathogens. The ultrafiltration membrane has the capacity to retain bacteria and some types of viruses (Rodríguez et al., 2011) and to operate at higher suspended biomass concentrations, which results in higher sludge retention times (SRT) as well as lower sludge production, avoiding problems of sludge

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bulking (Ahl et al., 2006). However, the poor characteristics of the sludge in the bioreactor (such as bulking of sludge due to excessive development of filamentous bacteria) can have a huge impact on membrane fouling, contributing to a worsening of the system performance (Meng et al., 2007; Meng and Yang, 2007). Fouling is a common problem of this kind of system; it is caused by the accumulation of substances on the surface of the membrane with a consequent reduction in membrane permeability (Defrance et al., 2000). Moreover, fouling is also related to particle and solute deposition inside the membrane pores; indeed, fouling can be usually divided into reversible, irreversible, and irrecoverable types (Judd, 2006).

On the other hand, biofilm processes have been proved to be reliable in organic matter and nutrients removal without suffering the typical problems of suspended biomass processes (Ødegaard et al., 1994). Biomass immobilisation as biofilm is an efficient method of retention of slow-growing microorganisms, such as nitrifiers (Kermani et al., 2008). The higher surface area of carriers in biofilm processes provides a higher number of sites for the adsorption and growth of microorganisms. Indeed, attached growth systems are generally considered less sensitive to toxic compounds and variations of environmental conditions (Wang et al., 2005). In this sense, biofilm technology, based on the use of plastic carriers with a lighter density than water which moves freely inside the bioreactor, is being successfully studied. It is called hybrid moving bed biofilm reactor (hybrid MBBR) or pure moving bed biofilm reactor (pure MBBR) technology, depending on whether or not suspended biomass is present. Immersed carriers are gradually colonised by the attached biomass; this biomass grows as a biofilm on these small elements, which move freely inside the bioreactor. This makes it possible to transport the substrates to the biofilm and to maintain a low biofilm thickness by shearing forces (Rusten et al., 2006). Hybrid MBBR has emerged as a highly effective biological process offering an alternative compact treatment to conventional activated sludge reactors for municipal and industrial wastewater treatment (Ødegaard et al., 1994). These systems combine suspended biomass and biofilm processes inside the biological reactor for biofilm growth (Ødegaard, 2006). Therefore, they include the positive aspects of the growth of suspended and attached biomass. In contrast to most biofilm processes, the whole volume can be used for biomass growth (Ferrai et al., 2010). In fact, this process has been proved to be a very simple and efficient technology in municipal wastewater treatment (Hem et al., 1994; Rusten et al., 1995). In regard to this, interesting results have been obtained showing the effectiveness of hybrid MBBR systems for organic matter and nutrients removal (Müller, 1998; Di Trapani et al., 2008).

Referring to MBR systems, the addition of carriers inside the bioreactor allow to reduce the concentration of suspended solids thus limiting the extent of membrane fouling, reducing the effect of membrane fouling caused by high biomass concentrations inside the membrane bioreactors (Leiknes and Ødegaard, 2001, 2002). Indeed, high mixed liquor suspended solids (MLSS) concentrations and flux of the membrane can severely affect the membrane fouling in MBR processes (Poyatos et al., 2008; Rahimi et al., 2011). An alternative way of solving this problem, which reduces the concentration of suspended biomass without limiting the efficiency of the process, is the use of a hybrid system in which a hybrid MBBR coupled with a MBR is used for the biodegradation of soluble organic matter. Indeed, the hybrid MBBR–MBR system has the potential of bringing together the best characteristics of biofilm processes and membrane separation (Ivanovic and Leiknes, 2008). In summary, in comparison to MBR, hybrid MBBR–MBR has the advantage of being even more compact, operating with higher fluxes, and having better energetic efficiencies and a higher control of membrane fouling, so this technology provides optional strategies for minimising the problem of fouling (Ivanovic et al., 2008).

Scale-up is a procedure for the design and construction of a large-scale system on the basis of the results of experiments with small-scale equipment, requiring a careful analysis of the influence of the operational conditions on the biological behaviour of the system (García-Ochoa and Gómez, 2009). The establishment of relationships for scale-up can be difficult due to the lack of sufficient data over a range of processing conditions (Junker, 2004), so it is necessary to carry out previous small-scale tests to establish the optimum conditions of a biological process. The necessary costs in the development of bioprocesses can be reduced by the use of the scale-up (Lamping et al., 2003; Gill et al., 2008; Li et al., 2008). Bioprocesses are usually developed in three stages or scales (Ju and Chase, 1992): (i) bench or laboratory scale, where basic screening procedures are carried out; (ii) pilot plant scale, where the optimal operational conditions are ascertained; and (iii) real plant scale, where the process is brought to an economic fruition.

A useful tool to analyse the scale-up is modelling. The modelling of biological processes makes it possible to describe and verify the kinetic processes which take part in the biological treatment of wastewater. Moreover, it is a very useful tool to predict the behaviour of the biological processes, applicable to their design, evaluation, and control. Kinetic modelling currently represents a helpful tool for characterising the kinetic behaviour of biological wastewater treatment systems by providing kinetic and stoichiometric parameters for heterotrophic and autotrophic biomass. It has become an important tool for engineers working in biological wastewater treatment (Martín-Pascual et al., 2013). Activated sludge models have been proved to have a wide application in the field of engineering (Gernaey et al., 2004; Drewnowski and Makinia, 2013). However, biofilm models have fewer direct applications and there is a gap between biofilm research and engineering practice in biofilm modelling (Plattes et al., 2008). Hybrid systems such as hybrid MBBR–MBR are relatively novel, and although in the last years several efforts have been made to improve the knowledge about the modelling of hybrid biomass (Lee, 1992; Sriwiriyarat and Randall, 2005; Boltz et al., 2009a, 2009b; Mannina et al., 2011), there are still some uncertainties concerning their kinetic behaviour. Competition can arise between the suspended and attached biomass for the availability of the substrates. As a consequence, modification of the kinetic parameters of both kinds of biomass occurs, compared to processes involving pure suspended or attached biomass (Di Trapani et al., 2010b).

Bearing in mind these considerations, the aim of this research was to analyse the effectiveness of the scale-up regarding organic matter removal in an innovative technology, hybrid MBBR–MBR, for treating wastewater through the kinetic behaviour of the heterotrophic biomass at two different scales by comparing their kinetic parameters.

2. Materials and methods

2.1. Experimental procedure

2.1.1. Description of the experimental plants

In this research two experimental plants with the same technology, configuration, and feed wastewater but different scales (Table 1) and locations were used. Hybrid MBBR–MBR_L was located in the Environmental Engineering Laboratory of the University of Granada, while hybrid MBBR–MBR_P was situated in a WWTP from Granada (Spain). Both plants were fed with wastewater taken from the outlet of the primary settler of a WWTP from Granada (Spain). The feeding of hybrid MBBR–MBR_L took place through a feeding tank filled daily with wastewater taken from the