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An integrated mathematical model for chemical oxygen demand (COD) removal in moving bed biofilm reactors (MBBR) including predation and hydrolysis

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ABSTRACT

An integrated mathematical model is proposed for modelling a moving bed biofilm reactor (MBBR) for removal of chemical oxygen demand (COD) under aerobic conditions. The composite model combines the following: (i) a one-dimensional biofilm model, (ii) a bulk liquid model, and (iii) biological processes in the bulk liquid and biofilm considering the interactions among autotrophic, heterotrophic and predator microorganisms. Depending on the values for the soluble biodegradable COD loading rate (SCLR), the model takes into account a) the hydrolysis of slowly biodegradable compounds in the bulk liquid, and b) the growth of predator microorganisms in the bulk liquid and in the biofilm. The integration of the model and the SCLR allows a general description of the behaviour of COD removal by the MBBR under various conditions. The model is applied for two in-series MBBR wastewater plant from an integrated cellulose and viscose production and accurately describes the experimental concentrations of COD, total suspended solids (TSS), nitrogen and phosphorous obtained during 14 months working at different SCLRs and nutrient dosages. The representation of the microorganism group distribution in the biofilm and in the bulk liquid allow for verification of the presence of predator microorganisms in the second reactor under some operational conditions.

1. Introduction

A moving bed biofilm reactor (MBBR) is a type of biofilm technology used for wastewater treatment (Kaindl, 2010). In such a reactor, the biomass grows as a biofilm on small carrier elements that move around in the reactor maintaining the biomass per unit volume at a high level. In aerobic processes, the biofilm carrier movement is effected by blowers. Therefore, the MBBR process has the advantages of attached and suspended growth systems (Qiqi et al., 2012). A key characteristic of MBBR reactors is not only the increase in the effective carrier area that thereby directly contributes to a larger biofilm but also that it allows good conditions for the transport of substrates into the biofilm (Mašic et al., 2010). Because of the extremely compact high-rate process, the hydraulic retention time (HRT) in the MBBR is low (Ødegaard, 2006). Moreover, it is a continuously operating, non-cloggable biofilm reactor with no need for backwashing, low head-loss and a high specific biofilm surface area (Rusten et al., 2006).

MBBR technology has been successfully applied to many types of wastewater including paper mill wastewater (Hosseini and Borghei, 2005), pharmaceutical industry wastewater (Lei et al., 2010), municipal wastewater (Rusten et al., 1998), and fish farm wastewater (Rusten et al., 2006) and has been utilized under aerobic and anoxic conditions (Barwal and Chaudhary, 2014; Borkar et al., 2013).

Different applications require different configurations using one or more reactors in-series for COD removal, nitrification and nutrient removal (Ødegaard, 1999). The type of microorganisms in these reactors depends on the conditions under study such as the origin of the wastewater, the treatment process, and the nutrient dosage, among others.

Modelling is an important step for the synthesis, design and decision making related to wastewater treatment processes. For biological wastewater treatment, a mathematical model can be

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used to predict the performance of a biological treatment plant, to determine important variables and critical parameters and/or to help with troubleshooting. A model that describes the MBBR process must include the biological processes in the biofilm and the bulk liquid because the biomass exists in two forms, suspended and attached to a carrier.

For general purposes, the biofilm model by Wanner and Gujer is a great tool for understanding biofilm processes in a quantitative manner (Wanner, 1996). Moreover, this type of model is generally adequate to describe a macroscopic conversion (Wanner et al., 2006) in a biofilm system and gives a reasonable description of the layered biofilm structure (van Loosdrecht et al., 2002; Mašic, 2013). Biological processes describing the interaction between autotrophic and heterotrophic microorganisms are commonly considered by activated sludge models (ASM).

The ASM models consider bacteria as the sole active biomass. The activities of all other microbial community members (protozoa, metazoa, phages, etc.) are hidden in a simple decay process responsible for the reduction of active biomass. This decay process is the sum of several independent processes such as maintenance, lysis due to phage infection and predation (van Loosdrecht and Henze, 1999).

The inclusion of predation is not necessary for the successful use of current activated sludge models (Moussa et al., 2005). However, the role of predators clearly affects the performance of a treatment plant and can be especially critical for obtaining a good quality effluent with low suspended solids (Tamis et al., 2011). In the moving bed process, the type of biofilm that develops depends on the organic loading rate applied (van Haandel and van der Lubbe, 2012). Kinner and Curds, 1987, examined the predators communities inhabiting RBC biofilms exposed to various organic loading rates; predators were observed mainly in compartments with low loadings.

Despite many studies of the microbial ecology of activated sludge systems and mathematical modelling, little work has been reported on the interaction between bacteria and other microorganisms in the microbial community of activated sludge, especially the role of protozoa (van Loosdrecht and Henze, 1999). The role of protozoa in activated sludge has been investigated by authors such as Moussa et al., 2005; Ni et al., 2009, 2011; Hao et al., 2011, who developed a simple procedure for the determination of the activity of these predators in suspended mixed cultures. These authors proposed a model to describe a mixed culture in which bacteria and predators (protozoa and metazoa) coexist. In this paper, the predation process is based on the studies of Moussa et al., 2005 and Hao et al., 2011, that simplify the description of the complex reality of the predator-prey relationship, including all types of predators in a single type and assuming that the predation process is a function of the bacterial concentration.

However, no work has included the predation phenomena in a mathematical model for an MBBR. Taking into account the different origins and characteristics of wastewater that can be treated in an MBBR plant and the different possible plant configurations, a general model of an MBBR process requires the inclusion of the predation mechanism.

This work presents a model that considers the interaction between bacteria and predator microorganisms in the MBBR process. The integrated mathematical model for MBBR proposed in this work combines the following: (i) biological processes describing the interaction between autotrophic, heterotrophic and predator microorganisms via the model of Moussa et al., 2005; (ii) a biofilm model by Wanner and Gujer, 1986; and (iii) a bulk liquid model (Mašic et al., 2010). Because the proposed model can be useful for wastewaters of different origins, plant configurations and operational conditions, the SCLR values (soluble COD loading rate) proposed by Ødegaard (1999) are taken into account to consider the predation growth mechanism in an MBBR reactor. Similarly, the reference values proposed by Helness and Ødegaard (2005), are taken into account to consider the hydrolysis in the bulk liquid. Finally, the regeneration of nutrients due to predators is also considered in the model (Lindblom, 2003).

Wastewater from the pulp and paper industry is characterized by a high COD content that can range from approximately 1000 to 4200 mg/l (Swamy et al., 2011). In general, this type of wastewater contains lignin (40%), carbohydrates (40%) and extractives (20%). The activated sludge process is one of the most common systems for the biological treatment of pulp and paper industry effluent; however, the main disadvantage of an AS process is the bulking of the sludge (Rankin et al., 2007). The pre-treatment of wastewater that has a high organic load with biofilm formation systems such as MBBR is used to control the phenomenon of bulking. In the pulp and paper industry, modelling of a biological treatment plant can be used to develop more efficient operational conditions and can help determine a more efficient nutrient dosage (Boltz et al., 2011; Lindblom, 2003).

In this work, the proposed model is applied to a full-scale MBBR plant that treats wastewater from a cellulose and viscose industrial plant with large amounts of organic matter.

2. Integrated mathematical model for MBBR

The integrated mathematical model presented in this paper is a multi-species and multi-substrate biofilm and bulk liquid model for an MBBR reactor.

The state variables of the integrated model proposed are composed of the concentrations of soluble compounds (S_i) and particulate compounds (X_i) (Henze et al., 2000). The nomenclature for the model state variables is given in Table 1.

The integrated mathematical model takes into account biological conversion processes observed in Fig. 1, which describes the transformation process and the interactions between three groups of microorganisms (i.e., autotrophs, heterotrophs and predators). The stoichiometric matrix and process rate equations for all of the processes in the integrated mathematical model can be found in Table 2 and Table 3, respectively, and the kinetic, stoichiometric and other parameters used in the integrated model are described in Table 4.

All particulate compounds in the model have been expressed as COD fractions, except for solids $X_{cellulose}$. The conversion between COD and total suspension solids (TSS) has been evaluated assuming stoichiometric conversion parameters of 0.75 and 0.90 gTSS/g COD (Boltz et al., 2011). TSS, filtered COD (COD_f) and total nitrogen (TN) have not been introduced as variables but were computed from the state variables by Equations (1, 2 and 3), respectively.

$$TSS = \Big(0.75\ X_I + 0.75\ X_S + 0.90\ X_H + 0.90\ X_{Aut} + 0.90\ X_{predators}\Big) + X_{cellulose} \tag{1}$$

$$COD_f = S_F + S_A + S_I \tag{2}$$

$$TN = S_{NO3} + S_{NH4} + S_{ND} \tag{3}$$

2.1. Biological processes

2.1.1. Predator growth

The impact of predator microorganisms has been investigated in MBBR microbial communities, and it has been found that even