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The role of interactions of effective biofilm surface area and mass transfer in nitrogen removal efficiency of an integrated fixed-film activated sludge system

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HIGHLIGHTS

- A 1-D mixed-culture biofilm model was developed to simulate the IFAS performance.
- The model reproduced long-term performance of both nitrification and denitrification.
- Model simulation revealed biofilm on the carriers functioned as reserved capacity.
- Microbial composition in the biofilm matrix was influenced by the COD load.
- Mass transfer and effective biofilm surface largely impacted overall IFAS performance.

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ABSTRACT

A reaction-diffusion biofilm model was implemented to simulate the nitrification/denitrification performance of a lab-scale integrated fixed-film activated sludge (IFAS) reactor. The model was capable of representing the system performance, i.e. changes in organic load and decrease in sludge age. Furthermore, nitrification batch tests with sludge and carrier material could also be simulated successfully with the model. Model simulation revealed that the diffusive fluxes into biofilm depended strongly on substrate loading as well as sludge age. The microbial composition in the biofilm matrix was mainly influenced by the diffusive flux of chemical oxygen demand (COD) into biofilm. When COD removal started to switch to biofilm, heterotrophic bacteria quickly replaced the previously dominating autotrophic bacteria. Running a set of simulations with a range of effective biofilm surface area and different mass transfer coefficients revealed the strong influence of these two parameters on the IFAS performance. The analysis showed that both parameters were dominating factors for ammonium removal. The optimum mass transfer coefficient was in the range of 3–4 m d^{-1} and the effective biofilm surface was around 63–88% of the theoretical carrier surface.

1. Introduction

Stringent effluent quality requirements with respect to nutrient removal, increased load into existing wastewater treatment plants (WWTPs) due to population growth, and the increase in the value of land raise the demand for retrofit of municipal WWTPs [1]. The Integrated fixed-film activated sludge system (IFAS) is an interesting alternative for the upgrade of existing activated sludge systems to meet a higher effluent quality and treatment capacity without requiring expansion in the footprint of the overall treatment process [2]. The process incorporates attached biomass on free floating carrier material with high surface area into an existing activated sludge plant to augment the amount of biomass available in the system and thereby stabilize nitrification by increasing sludge age. As the IFAS does not increase the suspended biomass, an overload of the secondary clarifier can be prevented [3]. The process combines the advantages of both, suspended activated sludge systems (flexibility and high degree of treatment) and attached growth (stability and resistance to organic and hydraulic shock loadings) [4]. The addition of carrier material provides protected interfaces for biofilm to grow on, thereby avoiding washout, which is of particular importance for the slow growing nitrifying bacteria [5]. Such improvement of the nitrification performance in

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municipal wastewater treatment plants has been reported by several researchers [6–8].

Bench-scale and full-scale studies have been conducted on the promising IFAS process, with the focus on the effects of suspended solid retention time (SRT), dissolved oxygen (DO) and carbon-to-nitrogen (C/N) ratio, and other operation parameters which are easy to measure experimentally [9–14]. In contrast, there is little information available to describe how biofilm surface area and mass transfer affect the IFAS performance due to the difficulty in experimental measurement, though they are considered as key parameters in the IFAS design [15].

Mathematical modeling of wastewater treatment processes is of great importance toward a full understanding of the complex system and the optimization of the design and operational parameters [14]. Although the combination of suspended sludge and fixed-film in an IFAS process introduces additional complexity to the modeling of the activated sludge process due to the more pronounced distribution of slow and fast growing microorganisms along the biofilm axis [16], several models have been developed to simulate the performance and the interaction of fixed growth and suspended growth [17–20]. These provided a better understanding of the intrinsic connections between biomass properties and process performance in IFAS systems [21].

Biofilm surface area is an important factor that influence the pollutant removal capacity of IFAS systems. It has been pointed out that the design value of the IFAS process is most correctly based on the effective biofilm surface area [15]. Sen et al. [22] also recommended that the concept of 2-D modeling is important in IFAS and moving bed biofilm reactor (MBBR) due to the loss in specific surface area on the inner surface of the carriers. The Unified Model for Activated Sludge, IFAS and MBBR systems developed by Sen and Randall [23] computes the biofilm surface area required to achieve the above stated objectives based on the plant loading, mixed liquor temperature and aerobic mixed liquor mean cell retention time. In Boltz et al. [19] fixed effective biofilm carrier's specific surface area was used throughout the manuscript to evaluate the model developed for IFAS/MBBR. However, the reduction of surface area available due to biofilm growth was not considered. All in all, there is still no biofilm model that addresses the impact of biofilm surface area change (e.g., reduction) with biofilm growth, probably due to complex carrier geometry, the inherent complexity with biofilm surface morphology, and the lack of methodologies accessing the real biofilm surface area correctly.

Also, it is well known that biofilm growth strongly depends on mass transfer at the bulk/biofilm interface [24]. Recent research in other biofilm systems has shown insight of the impact of biofilm carriers on mass transfer on related biochemical transformation processes [25,26]. Few researches have attempted to study the impact of mass transfer at the bulk/biofilm interface on the IFAS performance, although diffusion profile analysis has revealed the oxygen and ammonium diffusion limitation in the IFAS biofilm [21]. Due to the high DO and mixing requirements, the IFAS reactors were characterized by elevated air flux compared to activated sludge systems [8]. High aeration intensity in IFAS process requires further understanding and optimization to reduce its energy footprint, which can be achieved through modeling approach.

The sensitivity of parameters such as growth rate, half saturation constant and yield coefficient in biofilm models has already been described [27,28]. The aim of this work is to advance understanding and knowledge of the mechanism of the IFAS performance and biomass growth on the available biofilm surface area and resulting mass transfer using modeling approach. In this study, a lab-scale IFAS system was operated for 146 days with varying organic loading and sludge age. Based on the experimental data, a 1-D multi-species, diffusion biofilm model was developed in AQUASIM [29] to reproduce the data of the long-term system performance, and nitrification capacity in both biofilms/sludge. The model was then applied to simulate biomass growth and investigate the optimal conditions for achieving a high level of ammonium removal with varying effective biofilm surface area and mass transfer coefficient.

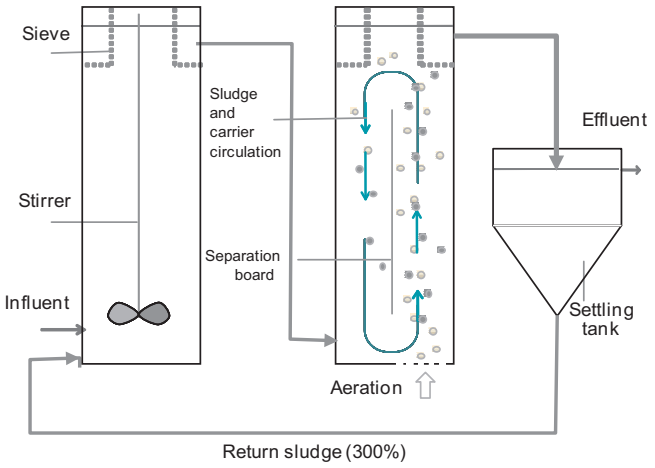

Fig. 1. Configuration of the lab-scale IFAS system (from left to right: R1, R2 and settling tank).

2. Material and methods

2.1. Reactor

In Fig. 1, the configuration of the lab-scale IFAS system is shown. The system consisted of a storage tank (not shown) and three 30 L tanks (R1, R2 and settler) operated at ambient temperature (20 °C) throughout the experimental period. Raw wastewater from WWTP Garching, Germany, first flew into a settling tank with a retention time of 30 min followed by the continuously stirred storage tank. The feed into the lab-scale IFAS system was provided constantly by a peristaltic pump. From left to right, the pre-denitrification tank (R1) was operated under anoxic conditions and mechanically stirred. Nitrification took place in the second tank (R2), where biofilm carriers were added after an initial phase (around 100 days). By aerating only one side of the board, which was installed in R2, the desired loop-flow and successful fluidization of the carriers was realized. Sludge circulation was controlled by a peristaltic pump to achieve 300% of return sludge corresponding to the volumetric influent flow rate. Sludge was wasted once a day in order to reach the desired sludge age (see Table 1).

The system was inoculated with 30 L of activated sludge from the WWTP Garching. In order to analyse the influence of solids retention time (SRT) and organic loading, the operation was divided into different phases (see Table 1). After the initial stage without carrier material, 7 L of biofilm carriers with a specific surface area of 650 $m^2\,m^{-3}$ were added into R2. Aeration was only supplied to R2. Oxygen concentration was kept at 7.6 ± 0.7 $mg\,L^{-1}$ as volumetric air flow was mainly used to fluidize the carrier material. After the addition of the carrier material the flow rate was stepwise increased to increase both COD and ammonium load. At the same time, the SRT was decreased from 20 days to 5 days, as given in Table 1.

2.2. Batch experiments

The nitrification capacity of activated sludge and biofilm carriers was determined in batch experiments in 1 L beakers and conducted at defined conditions in parallel to the continuous reactor operation. For activated sludge, 100 mL stock solution with a concentration of 6 $g\,L^{-1}$ ammonium bicarbonate (NH_4HCO_3) was added into 900 mL sludge sample directly taken from the reactor tank R2. For the batch test with carrier material, 121 pieces of carriers (about 233 mL) were taken out of the reactor tank R2, washed with tap water, and added into a 1 L beaker with a solution of 900 mL tap water mixed with 100 mL stock