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Simulation of heterotrophic storage and growth processes in activated sludge under aerobic conditions

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Abstract

In this work, an extension of the Activated Sludge Model No. 3 (ASM3) is presented which takes oxygen transfer, microbial maintenance, and biomass decay into account, in order to describe the heterotrophic storage and growth processes in activated sludge. The sensitivity of the effluent chemical oxygen demand and oxygen uptake rate to the stoichiometric and kinetic coefficients was analyzed. Model calibration was successfully performed by comparing measured and predicted values for model components. Thereafter, the model was evaluated with the experimental results of four independent case studies. Results show that the established model is able to better and mechanistically describe the heterotrophic storage and growth processes in activated sludge.

Keywords: Activated sludge; Activated Sludge Model No. 3 (ASM3); Chemical oxygen demand (COD); Growth; Modeling; Oxygen uptake rate (OUR); Storage

1. Introduction

Mathematical modeling is useful exercise for understanding and optimizing substrate utilization by microorganisms in complex systems. Model simulations can provide a solid foundation for design and operation of various biological treatment systems. For the activated sludge process, modeling has gained significant popularity in the past decades. The activated sludge model suite established by the International Water Association Task Group [1] has provided a standardized set of basic models for biological wastewater treatment processes. These models have been widely accepted in the scientific community and used by the environmental engineers. It has evolved from a simple growth-based kinetics model, Activated Sludge Model No. 1 (ASM1) [2], to a more complicated model involving the description of storage phenomena, i.e., Activated Sludge Model No. 3 (ASM3) [3].

The ASM1 was developed primarily for municipal treatment plants using activated sludge process to describe the removal of organic carbon and ammonium-N. The subsequent ASM3 [1,3] was established for overcoming a number of shortcomings that have emerged from its applications, focusing on biological N removal [4]. The main reason behind such a shift is the increasing understanding on the important role of storage polymers as an essential intermediate in the overall substrate removal by activated sludge, in particular when activated sludge is alternatively subjected to feast and famine conditions [5–7].

However, when ASM3 is used to interpret the data obtained in short-term respirometric batch experiments, inconsistencies often arise [5]. In order to keep the modeling simple [3], in ASM3 it is assumed that all readily biodegradable substrate is initially stored as internal storage products before it is used for growth at the famine phase. However, this is not true in many cases. Krishna and van Loosdrecht [5] found that ASM3 was not appropriate in two cases: one was the discontinuity in the biomass growth rate observed experimentally at feast and famine phases, while another was that it required prediction of a higher level of internal storage polymers than the measured to fit the oxygen consumption. In actual situations storage and growth occur simultaneously at the feast phase, as opposed to the assumption of ASM3, in which only storage occurs at the feast phase [5]. Thus, it was suggested that the simultaneous storage and growth should be taken into account for a better interpretation of the experimental results [5]. Thus, it becomes clear that ASM3 should be extended to account for the simultaneous storage and growth occurring in activated sludge.

Therefore, in this work a generalized model considering simultaneous storage and growth processes in activated sludge

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under aerobic conditions is established. In this model oxygen transfer, microbial maintenance, and biomass decay are all taken into account. A sensitivity analysis on the model parameters is performed to gain a better insight into the model structure. This model is verified by comparing the experimental and simulating results for four independent case studies. It is expected that the information provided in this work will be useful to improve our understanding on the storage and growth processes in activated sludge.

2. Model development

The ASM3 model was modified to introduce simultaneous substrate storage and growth concept, considerations of microbial maintenance processes, and oxygen transfer. This extension of ASM3 model is structured with seven model components or state variables, including dissolved oxygen (DO), S_O; readily biodegradable substrate, S_S; ammonia, S_{NH_4}; slowly biodegradable substrate, X_S; heterotrophic biomass, X_H; particulate inert COD, X_I; and storage products of active heterotrophic biomass, X_{STO}. The model considers seven microbial processes: hydrolysis of slowly biodegradable substrate, growth on readily biodegradable substrate, aerobic storage of readily biodegradable substrate, growth on storage products, maintenance on readily biodegradable substrate, maintenance on storage products, biomass decay, and oxygen transfer. Related process kinetics and stoichiometry describing the interactions and transformations among model components are expressed in a way that is compatible with previous mathematical models for formulating biochemical reactions of activated sludge [1–3].

The structure of the proposed model is presented in a matrix format [1] reflecting the basic stoichiometric relationships constituting the backbone of the model. The matrix format is outlined in Table 1, where model components are listed in the upper row; the rightmost column gives the process rate expressions; the relevant stoichiometric coefficients are incorporated in appropriate matrix cells. In this way, the rate of change (generation or utilization) in a model component for a given biochemical process is obtained by multiplication of related process stoichiometrics and kinetics [8].

A schematic framework is illustrated in Fig. 1 to describe the relationships among the different groups of components of the model. In this framework, the slowly biodegradable substrate in wastewater is first hydrolyzed to readily biodegradable substrate by the heterotrophs. The biomass can use it for simultaneous storage and growth. When the readily biodegradable substrate is depleted (as low as the half saturation concentration for the primary growth), the degradation (secondary growth) of the storage polymers takes place. In addition to growth, microbial maintenance on the external (S_S) and internal (X_{STO}) substrate is also an important compartment in this integrated model for describing storage and growth processes in activated sludge. Finally, biomass is subjected to decay and produces inert organic carbon.

As shown in Fig. 1, the simultaneous microbial storage and growth concept [9–10] is incorporated into the model in this work. This concept can be explained in such a way that the heterotrophs are capable of simultaneously storing the external

Table 1
Stoichiometric and kinetic matrix for the developed model

Process	Component							Kinetics rates expressions
	S_O O_2	S_{NH_4} N	S_S COD	X_I COD	X_S COD	X_H COD	X_{STO} COD	
1. Hydrolysis			1		−1			$k_H \frac{X_S/X_H}{K_X+(X_S/X_H)} X_H$
2. Storage	$-\frac{1-Y_{STO}}{Y_{STO}}$		$-\frac{1}{Y_{STO}}$				1	$k_{STO} \frac{S_S}{K_S+S_S} \frac{S_O}{K_O+S_O} X_H$
3. Growth on S_S	$-\frac{1-Y_{H,S}}{Y_{H,S}}$	$-i_{NBM}$	$-\frac{1}{Y_{H,S}}$			1		$\mu_{H,S} \frac{S_S}{K_S+S_S} \frac{S_O}{K_O+S_O} \frac{S_{NH_4}}{K_{NH_4}+S_{NH_4}} X_H$
4. Growth on X_{STO}	$-\frac{1-Y_{H,STO}}{Y_{H,STO}}$	$-i_{NBM}$				1	$-\frac{1}{Y_{H,STO}}$	$\mu_{H,STO} \frac{K_S}{K_S+S_S} \frac{S_O}{K_O+S_O} \frac{S_{NH_4}}{K_{NH_4}+S_{NH_4}} \frac{X_{STO}/X_H}{K_{STO}+(X_{STO}/X_H)} X_H$
5. Maintenance on S_S	−1		−1					$m_{H,S} \frac{S_S}{K_S+S_S} \frac{S_O}{K_O+S_O} X_H$
6. Maintenance on X_{STO}	−1						−1	$m_{H,STO} \frac{K_S}{K_S+S_S} \frac{S_O}{K_O+S_O} \frac{X_{STO}/X_H}{K_{STO}+(X_{STO}/X_H)} X_H$
7. Decay		$i_{NBM} - f_I i_{NXI}$		f_I	$1-f_I$	−1		$b_H \frac{K_S}{K_S+S_S} \frac{K_{STO}}{K_{STO}+(X_{STO}/X_H)} X_H$