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Modelling the biological processes of MBR treatment plants

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ABSTRACT

The paper proposes the use of a new mathematical model to simulate the biological processes taking place in membrane bioreactors (MBR) treatment plants. The model adopts the easy-to use matricial formulation of traditional activated sludge models (ASM). It couples the death-regeneration hypothesis of ASM 1 with the storage approach of ASM 3 in order to take into account the alternation of nutrients abundance and shortage periods, which are characteristic of treatment plants operating with low food/biomass ratio, as typically MBRs are. Moreover, it considers the production and the consumption of soluble microbial products, which play a fundamental role in biological membrane fouling. Model's parameters are either measured through respirometric tests, or obtained through calibration on a pilot-scale plant, and successive validation on a full-scale plant. The model is limited to the biological phases, and therefore it can be coupled with any detailed model of the separation phase, resulting in very versatile practical uses.

Keywords: Activated sludge; Membrane bioreactors; Mathematical modelling; Soluble microbial products

1. Introduction

Although membrane bioreactors (MBRs) represent a well-established and appreciated solution for the treatment of municipal and industrial wastewaters due to their recognized advantages in terms of quality of the final effluent and the reduced size of the overall installation [1–7], there are still several aspects related to their design and exploitation that remain to be investigated in more detail. At this regard, the use of mathematical models aimed at process simulation can represent a useful tool. Referring to the biological processes taking place in MBRs, it is possible to adopt the same models generally used for the simulation of activated sludge systems (CASs), known as activated sludge models (ASMs) [8]. These models are in fact extremely detailed in terms of biochemical description. Nonetheless, having been developed for conventional

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CASs, they do not take into consideration the presence of membranes, which affect the biological processes as discussed by Visvanathan et al. [9] or more recently by Massé et al. [10]. Particularly these latter, comparing the organic removal efficiency between CAS and MBR systems, proved that the better performance of the second was only partly due to the suspended solids retention action operated by the membrane, as differences in proteins and polysaccharides production contributed to reach a different organic removal efficiency rate. To overcome these limitations several authors have modified ASMs and have adapted them taking into account the specificity of MBRs [11]. A recent and quite extended review of these models can be found in Zuthi et al. [12]. Generally the most advanced models specifically developed for MBRs include the production of soluble microbial products (SMPs) analyzing their effect on membrane performances [13,14], and are very detailed in terms of membrane filtration simulation [15–19]. Nonetheless, being almost always based on the first version of ASMs (ASM1), they do not take into account the storage of organic matter, which instead is very important in MBRs, because of the high concentration of biomass and the low food/biomass ratio, characteristic of these systems.

The model presented in this paper, instead, includes not only the production of SMPs, but also the storage of organic matter, maintaining the easy-to-use matricial structure of ASMs. The model is limited to the simulation of the biological phases of MBRs, and therefore does not include any simulation of the filtration phase. This choice meets the need of developing a mathematical tool having the following characteristics: it is easy to be calibrated and validated and can be applied and integrated with other mathematical modules. All kinds of different models of the filtration phase, e.g. those developed by Broeckmann et al. [20], Li and Wang [21], Busch et al. [22] and Khan et al. [23], can be actually coupled with it, whatever the adopted configuration of the membrane units, and whatever the type of used membranes. The model is calibrated using the experimental data obtained, at pilot-scale, on a treatment plant fed with synthetic wastewater, and is validated using the data obtained, at full-scale, on a treatment plant fed with municipal wastewater.

2. Model structure

As well-known ASMs represent a common platform on which the detailed simulation scheme for the specific considered plant adopting an activated sludge process is built. To propose a new model for MBRs, it is possible to start from this platform, but it is also required highlighting the specificities coming from the substitution of the settling phase with a membrane filtration one [12]. One of the peculiarities of MBRs is the alternation of periods of nutrients abundance and nutrients shortage. This is due to the high biomass concentration, compared to the amount of influent organic matter, maintained in these systems. As a consequence of this alternation, heterotrophic micro-organisms are pushed to implement a mechanism of substrate storage, and to use the stored reserve for their metabolic activities. Therefore storage mechanisms should be included in MBRs model construction. Another element, which cannot be neglected in the operative conditions of MBRs, is the accumulation of SMPs in the biological tanks. SMPs can be divided into two groups [24,25]. The first one includes the so-called utilization-associated products (UAPs), which are simple molecules, mainly composed of carbon, associated to the organic matter metabolism. The second group, instead, includes the so-called biomass-associated products (BAPs), which are complex molecules composed of carbon and nitrogen, associated to the biomass decay. The membrane can retain both UAPs and BAPs, which tend to accumulate in the biological tanks, and contribute to the biological fouling of the separation units. The prediction of UAPs and BAPs concentration is therefore a relevant part of model simulation of biological processes taking place in MBRs. Considering the over-mentioned peculiarities of MBRs, the proposed approach for biological model simulation makes use of the base version of ASMs, usually indicated as ASM1, integrating it with the storage process of organic matter, included in the third version of ASMs (ASM3), and with the process of SMPs formation (Lu-SMP model [13]). It should be mentioned that, similarly to ASM1, the proposed model assumes the death-regeneration approach for biomass decay [26]. This aspect is extremely important for the evaluation of the kinetic constants using traditional respirometric techniques [27,28]. Overall the model includes 14 biological processes, which are (Fig. 1): (i) aerobic and (ii) anoxic storage of soluble organic substrates; (iii) aerobic and (iv) anoxic storage of SMPs; (v) aerobic and (vi) anoxic growth of heterotrophic micro-organisms (HMs) using the stored substrates; (vii) aerobic growth of autotrophic micro-organisms (AMs); decay of HMs with the formation of (viii) suspended organic matter and (ix) BAP; decay of HMs with formation of (x) suspended organic matter and (xi) BAP; (xii) aerobic and (xiii) anoxic hydrolysis of suspended organic matter; (xiv) decay of stored substrates. HMs store the soluble organic matter present in the influent wastewater together with the one produced by microbial processes (SMPs). The growth of HMs takes place oxidizing the stored substrates. The final electrons acceptor of the process can be either the oxygen

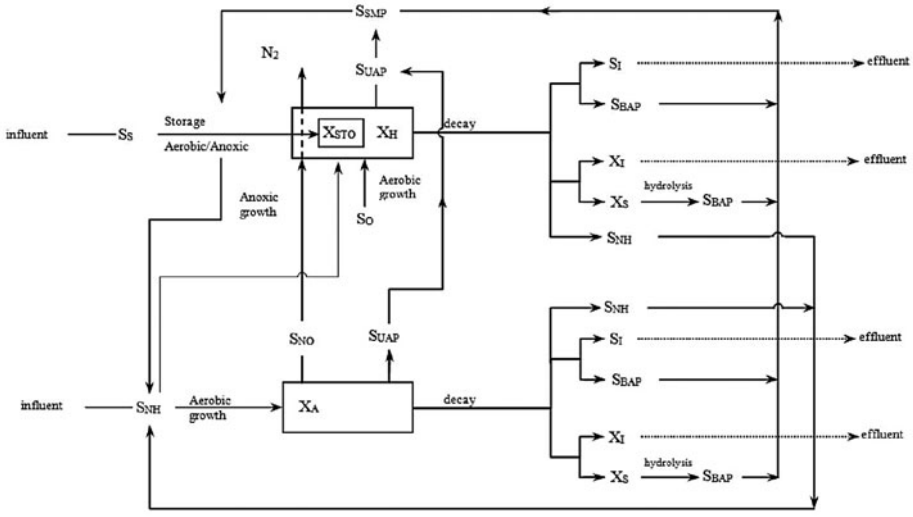

Fig. 1. MBR model flow chart.

(aerobic growth) or the nitrate (anoxic growth). As a consequence of the metabolic activity of HMs, some organic compounds overall indicated as UAPs are produced. AMs grow up consuming the influent ammonia nitrogen, and using the oxygen as final electrons acceptor (aerobic growth). The final products of their metabolic activity include both UAPs and nitrates. As a consequence of HMs and AMs death, soluble and particulate substances, both organic and inorganic, are released. The inorganic by-products exit the system with the effluent. The organic ones, instead, indicated as BAPs, are recycled, in agreement with the death-regeneration assumption. Of course all organic particulate compounds are subject to hydrolysis before utilization. Process kinetics are those already introduced in the ASM1, ASM3, and Lu-SMP model (Table 1). The resulting matricial representation of the model is summarized in Fig. 2 where the 3rd, 4th, 9th, 11th, and 14th processes are derived from Lu-SMP model and integrated to the others already present in ASMs.

Table 1
Adopted kinetic expressions

Process	Kinetic expression
Aerobic storage of S_S	$\rho_1 = k_{STO} \frac{S_s}{K_s + S_s} \frac{S_O}{K_{O,H} + S_O} X_H$
Anoxic storage of S_S	$\rho_2 = \eta_{NO} K_{STO} \frac{S_s}{K_s + S_s} \frac{S_{NO}}{K_{NO} + S_{NO}} X_H$
Aerobic storage of S_{SMP}	$\rho_3 = K_{STO} \frac{S_{SMP}}{K_{SMP} + S_{SMP}} \frac{S_O}{K_{O,H} + S_O} X_H$
Anoxic storage of S_{SMP}	$\rho_4 = \eta_{NO} K_{STO} \frac{S_{SMP}}{K_{SMP} + S_{SMP}} \frac{S_{NO}}{K_{NO} + S_{NO}} X_H$
HMs aerobic growth	$\rho_5 = \mu_H \frac{X_{STO}/X_H}{K_{STO} + X_{STO}/X_H} \frac{S_O}{K_{O,H} + S_O} X_H$
HMs anoxic growth	$\rho_6 = \eta_{NO} \mu_H \frac{X_{STO}/X_H}{K_{STO} + X_{STO}/X_H} \frac{S_{NO}}{K_{NO} + S_{NO}} X_H$
AMs aerobic growth	$\rho_7 = \mu_A \frac{S_{NH}}{K_{NH} + S_{NH}} \frac{S_O}{K_{O,A} + S_O} X_A$
HMs decay and formation of X_S	$\rho_8 = b_H X_H$
HMs decay and formation of BAP	$\rho_9 = b_{BAP,H} X_H$
AMs decay and formation of X_S	$\rho_{10} = b_A X_A$
AMs decay and formation of BAP	$\rho_{11} = b_{BAP,A} X_A$
Aerobic hydrolysis	$\rho_{12} = K_H \frac{X_s/X_H}{K_X + X_s/X_H} \frac{S_O}{K_{O,H} + S_O} X_H$
Anoxic hydrolysis	$\rho_{13} = \eta_H K_H \frac{X_s/X_H}{K_X + X_s/X_H} \frac{S_{NO}}{K_{NO} + S_{NO}} X_H$
X_{STO} decay	$\rho_{14} = b_{STO} X_{STO}$

	S_S	S_I	X_S	X_I	X_H	X_A	X_{STO}	S_{SMP}	S_{NO}	S_{NH}	Process rate
Aerobic storage of S_S	-1						$Y_{STO,O}$			$i_{N,SS}$	ρ_1
Anoxic storage of S_S	-1						$Y_{STO,NO}$		$-\left(\frac{1-Y_{STO,NO}}{2,86}\right)$	$i_{N,SS}$	ρ_2
Aerobic storage of SMP							$Y_{STO,O}$	-1		$i_{N,SMP}$	ρ_3
Anoxic storage of SMP							$Y_{STO,NO}$	-1	$-\left(\frac{1-Y_{STO,NO}}{2,86}\right)$	$i_{N,SMP}$	ρ_4
Aerobic growth of HMs					1		$-\frac{1}{Y_{H,O}}$	$\square_{UAP,H}$		-$i_{N,BM}$	ρ_5
Anoxic sgrowth of HMs					1		$-\frac{1}{Y_{H,NO}}$	$\square_{UAP,H}$	$-\left(\frac{1-Y_{H,NO}}{2,86\cdot Y_{H,NO}}\right)$	-$i_{N,BM}$	ρ_6
Aerobic growth of AMs						1		$\square_{UAP,A}$	$\frac{1}{Y_A}$	$-\left(i_{N,BM}+\frac{1}{Y_A}\right)$	ρ_7
Decay of HMs with formation of XI			1-f_P	f_P	-1					$i_{N,BM}$	ρ_8
Decay of HMs with formation of BAP		f_B			-1			1- f_B		$i_{N,BM}$	ρ_9
Decay of AMs with formation of XI			1-f_P	f_P		-1				$i_{N,BM}$	ρ_{10}
Decay of AMs with formation of BAP		f_B				-1		1- f_B		$i_{N,BM}$	ρ_{11}
Aerobic hydrolysis			-1					1			ρ_{12}
Anoxic hydrolysis			-1					1			ρ_{13}
Decay of XSTO							-1				ρ_{14}

Fig. 2. Matricial expression of the proposed model.

3. Experimental procedure

The pilot plant used for model calibration was configured in the pre-denitrification mode. It included a 13.6 L anoxic reactor for denitrification and a 30.8 L aerobic reactor for organic substrate oxidation and nitrification. The membrane unit (ZW10, Zenon) was plunged in the oxidation tank. The process was automatically controlled continuously, to maintain, as much as possible, steady state conditions. The synthetic wastewater having the same characteristics of a real municipal wastewater was prepared following the indication of Insel et al. [29]. The influent flow was fixed at 105 L d^{-1}, and the recycle flow at 315 L d^{-1}. Wastewater samples were withdrawn daily from each tank, and analyzed for the determinations of the parameters (listed in Table 2) used for the calibration. SMPs concentration was estimated through carbohydrates and proteins evaluation [14]. COD fractionation was effectuated according to Henze et al. [8]. The plant was operated for 10 months. After 6, 7, and 8 months of operations, 1 liter of sludge was withdrawn from each biological reactor for the determination of the main kinetic constants. With this aim, a LFS (liquid phase principle, flowing gas, static liquid) respirometer (SPES, Italy) was used. Kinetic constants were measured following the procedure reported in Spanjers and Vanrolleghem [27]. The same respirometer was used to measure the kinetic constants of the sludge withdrawn from the full-scale treatment plant and used for model validation. This plant was located in the province of Naples (south of Italy), and received the municipal wastewater produced in a small urban area of 2,300 inhabitants. The plant was configured in the pre-denitrification mode, and adopted the same

Table 2
Input data used for the calibration including values (i.e. last 6) obtained from respirometric tests

X_S	229 (gCOD m^{-3})
S_S	104 (gCOD m^{-3})
S_O	2.2 (g m^{-3})
X_I	15 (gCOD m^{-3})
S_I	5 (gCOD m^{-3})
S_{NO}	2 (gN-NO_3 m^{-3})
S_{NH}	53 (gN-NH_4 m^{-3})
S_{SMP}	68 (gCOD m^{-3})
V_N	30.8 (L)
V_D	13.6 (L)
Q_{in}	105 (L d^{-1})
Q_R	315 (L d^{-1})
μ_H	6 (d^{-1})
μ_A	0.8 (d^{-1})
b_H	0.15 (d^{-1})
b_A	0.03 (d^{-1})
$Y_{H,O}$	0.53 (gCOD $gCOD^{-1}$)
Y_A	0.25 (gCOD $gCOD^{-1}$)

membrane separation system mimicked in the pilot plant. Data concerning influent wastewater characteristics, reactors volumes and biological process performances, were obtained from the charged to manage the plant. Average values, referred to one month of activities of the plant, were used for the validation.

4. Model calibration and validation

The proposed model was calibrated using the experimental data obtained on the pilot plant previously described. Input data assigned for the calibration were (Table 2): characteristics of the influent wastewater; volumes of the tanks; operative parameters of the plants; and values of kinetic constants obtained from respirometric tests. On the basis of experimental data, the following percentages were assumed for the membrane unit: SMP retention 65%; organic particulate matter retention 100%; inert soluble matter retention 4%; and organic soluble matter retention 4%. Moreover, the following conversion coefficients were experimentally obtained: soluble chemical oxygen demand (COD) = 1.42 gCOD $gVSS^{-1}$; carbohydrates = 1.5 gCOD $gVSS^{-1}$; proteins = 1.07 gCOD $gVSS^{-1}$. All values used in the model were not very different from those published by Henze et al. [8] and Lu et al. [13].

The calibration was effectuated fitting the simulated values resulting from the model with the average values measured in the two biological reactors of the pilot-plant after 70 d of operation, when steady state conditions were reached. Fitting was performed iteratively using Simulink 8.1, starting from the calibration of parameters referred to the organic substrate, passing the obtained values in the equations simulating the nitrification and denitrification, and repeating the cycle minimizing the differences between measured and simulated values, until the differences were smaller than 5%. The final set of calibrated parameters is summarized in Table 3. The Table also lists the average values obtained from the available literature [8,13]. The listed values confirm the strength and accuracy of the model as they are really close to those used by Henze and Lu, respectively, to run the ASMs and the Lu-model. Small differences, however, never higher than one order of magnitude, were found for η_{NO} and K_S between the proposed model and ASMs and for $b_{BAP,H}$, b_{STO}, f_B, $\gamma_{UAP,H}$, and $\gamma_{UAP,A}$ between the proposed model and Lu-SMP model and they can be reasonably attributed to the specific operational conditions set for the experiments and the method used to calibrate the model.

Table 3
Results of calibration from simulation by Simulink and compared to literature average values

Parameter	Calibration	Average values
η_{NO} (dimensionless)	0.38	0.9
k_{STO} (gCOD $gCOD^{-1}$ d^{-1})	4.2	5
k_h (gCOD $gCOD^{-1}$ d^{-1})	3	3
K_X (gCOD/gCOD)	0.9	0.9
η_h (dimensionless)	0.4	0.4
K_{STO} (gCOD $gCOD^{-1}$)	1	1
$K_{O,H}$ (gO_2 m^{-3})	0.2	0.2
$K_{O,A}$ (gO_2 m^{-3})	0.5	0.4
K_{NOx} (gNO_x-N m^{-3})	0.6	0.5
K_S (gCOD m^{-3})	20	10
K_{SMP} (gCOD m^{-3})	106	/
K_{NH} (gN_4^+-N m^{-3})	0.95	1
$b_{BAP,H}$ (L d^{-1})	0.28	0.4
$b_{BAP,A}$ (L d^{-1})	0.1	0.1
b_{STO} (L d^{-1})	0.13	0.2
f_B (gCOD $gCOD^{-1}$)	0.033	0.005
f_P (gCOD $gCOD^{-1}$)	0.1	0.08
$Y_{H,NO}$ (gCOD $gCOD^{-1}$)	0.58	0.54
$Y_{STO,O}$ (gCOD $gCOD^{-1}$)	0.95	0.85
$Y_{STO,NO}$ (gCOD $gCOD^{-1}$)	0.85	0.8
$\gamma_{UAP,H}$ (dimensionless)	0.65	0.38
$\gamma_{UAP,A}$ (dimensionless)	1.25	1.6
$i_{N,SS}$ (gN $gCOD^{-1}$)	0.03	0.03
$i_{N,SMP}$ (gN $gCOD^{-1}$)	0.05	/
$i_{N,BM}$ (gN $gCOD^{-1}$)	0.0875	0.0875

Table 4
Input data used for the validation including values (i.e. last 6) obtained from respirometric tests

X_S	850 (gCOD m^{-3})
S_S	57 (gCOD m^{-3})
S_O	2 (g m^{-3})
X_I	94 (gCOD m^{-3})
S_I	30 (gCOD m^{-3})
S_{NO}	2 ($gN\text{-}NO_3$ m^{-3})
S_{NH}	57 ($gN\text{-}NH_4$ m^{-3})
S_{SMP}	63 (gCOD m^{-3})
V_N	346.1 (m^3)
V_D	98.6 (m^3)
Q_{in}	27.8 (m^3 d^{-1})
Q_R	138 (m^3 d^{-1})
μ_H	9 (d^{-1})
μ_A	0.5 (d^{-1})
b_H	0.21 (d^{-1})
b_A	0.04 (d^{-1})
$Y_{H,O}$	0.70 (gCOD $gCOD^{-1}$)
Y_A	0.85 (gCOD $gCOD^{-1}$)

Table 5
Comparison between simulated and measured values in the full-scale plant

Component of the model	Simulated	Measured
Aerobic tank		
S_{SMP} (gCOD m^{-3})	30.6	31.5
$S_S + S_{SMP} + S_I$ (gCOD m^{-3})	45.8	43.0
S_{NO} (gNO_3-N m^{-3})	46.1	37.7
S_{NH} (gNH_4-N m^{-3})	0.3	0.3
Anoxic tank		
$S_S + S_{SMP} + S_I$ (gCOD m^{-3})	61.1	61.2
S_{NO} (gNO_3-N m^{-3})	12.3	11.4
S_{NH} (gNH_4-N m^{-3})	14.0	17.2

The set of parameters reported in Table 3 was adopted to simulate the processes taking place in the full-scale plant, in order to validate the model. Input data used for the validation are summarized in Table 4. Data obtained from the model are reported, instead in Table 5 together with the average characteristics of the samples withdrawn from the full-scale plant. By comparing the two sets of data, it can be concluded that the results of validation were quite satisfying.

It has to be noted that the kinetic constants used, as input parameters, for the validation, were different from those used for the calibration. Both the series, in fact, were obtained through respirometric tests on the specific sludge sampled from the plant. This can be ascribed to the differences in the influent wastewater composition, and suggests the existence of differences also in other kinetic constants and stoichiometric coefficients, which instead were assumed to be the same. Nonetheless the obtained results indicate that the model is able to simulate closely enough the process development and therefore the effect of these differences can be considered negligible.

5. Conclusions

Results from the validation process have proven the accuracy of the proposed model in simulating the biological process that takes place in MBR systems. The phenomenon of nutrients' storage in the biomass cells during starving episode, included in the model, is therefore an essential element of the mechanisms that govern the substrate consumption in MBR systems and therefore it cannot be neglected in the MBR models. Besides this novelty, the proposed model also shows its potentiality in being easily coupled with other models that can take into account the hydrodynamics of the biological reactor as well as the physical and chemical processes that occur in it simultaneously with the biological degradation of biodegradable substances. Doubtlessly the model presented in this work can be really useful in designing and monitoring new MBRs treatment plant as well as updating already in service CAS plants.

List of symbols and abbreviations

MBRs — membrane bioreactors
CASs — activated sludge systems
UAPs — utilization-associated products
HMs — heterotrophic microorganisms
LFS — liquid phase priciple
VSS — volatile suspended solids
S_{SMP} (gCOD m^{-3}) — SMPs concentration
K_S (gCOD m^{-3}) — half saturation constant for Ss
X_H (gCOD m^{-3}) — heterotrophic biomass
η_{NO} (dimensionless) — anoxic process correction factor
K_{NO} (gNO_x-N m^{-3}) — half saturation constant for S_{NO}
μ_H (d^{-1}) — growth rate of X_H
μ_A (d^{-1}) — growth rate of X_A
K_{NH} (gNH_4^+-N m^{-3}) — half saturation constant for S_{NH}
X_S (gCOD m^{-3}) — biodegradable suspended matter
b_H (L d^{-1}) — decay rate of X_H coverted in X_S
b_A (L d^{-1}) — decay rate of X_A coverted in X_S
k_h (gCOD gCOD d^{-1}) — hydrolysis rate
η_h (dimensionless) — hydrolysis correction factor
b_{STO} (L d^{-1}) — decay rate of X_{STO}
f_B (gCOD $gCOD^{-1}$) — biomass inert fraction converted in S_I
$Y_{H,NO}$ (gCOD $gCOD^{-1}$) — biomass yield in denitrification
$Y_{STO,O}$ (gCOD $gCOD^{-1}$) — ox-storage process biomass yield
$\gamma_{UAP,H}$ (dimensionless) — UAP production from X_H
$i_{N,SMP}$ (gN $gCOD^{-1}$) — N content in X_{SMP}
V_N (m^3) — nitrification tank volume
Q_{in} (m^3 d^{-1}) — influent flowrate
$Y_{H,O}$ (gCOD $gCOD^{-1}$) — heterotrophic biomass yield
ρ_1 — aerobic storage of S_S
ρ_2 — anoxic storage of S_S
ρ_3 — aerobic storage of S_{SMP}
ρ_4 — anoxic storage of S_{SMP}
ρ_5 — HMs aerobic growth
ρ_6 — HMs anoxic growth
ρ_7 — Ams aerobic growth

ASMs — activated sludge models
SMPs — soluble microbial products
BAPs — biomass-associated products
AMs — autotrophic microorganisms
COD — chemical oxygen demand
S_S (gCOD m^{-3}) — soluble organic substrates
k_{sto} (gCOD $gCOD^{-1}$ d^{-1}) — storage rate
S_O (gO_2 m^{-3}) — dissolved oxygen
$K_{O,H}$ (gO_2 m^{-3}) — half saturation constant of S_O for X_H
S_{NO} (gNO_x-N m^{-3}) — sum of nitrate and nitrite
K_{SMP} (gCOD m^{-3}) — half saturation constant for S_{SMP}
X_A (gCOD m^{-3}) — autotrophic biomass
S_{NH} (gNH_4^+-N m^{-3}) — ammonium
$K_{O,A}$ (gO_2 m^{-3}) — half saturation constant of S_O for X_A
X_I (gCOD m^{-3}) — inert suspended matter
$b_{BAP,H}$ (L d^{-1}) — decay rate of X_H converted in S_S
$b_{BAP,A}$ (L d^{-1}) — decay rate of X_A converted in S_S
K_X (gCOD m^{-3}) — half saturation constant for hydrolysis
X_{STO} (gCOD m^{-3}) — stored matter in X_H
S_I (gCOD m^{-3}) — soluble inert matter
f_P (gCOD $gCOD^{-1}$) — biomass inert fraction converted in X_I
$Y_{STO,NO}$ (gCOD $gCOD^{-1}$) — anox-storage process biomass yield
$\gamma_{UAP,A}$ (dimensionless) — UAP production from X_A
$i_{N,SS}$ (gN $gCOD^{-1}$) — N content in X_S
$i_{N,BM}$ (gN $gCOD^{-1}$) — N content in X_H and X_A
V_D (m^3) — denitrification tank volume
Q_R (m^3 d^{-1}) — recirculated flowrate
Y_A (gCOD $gCOD^{-1}$) — autrotophic biomass yield
ρ_8 — HMs decay and formation of X_S
ρ_9 — HMs decay and formation of BAP
ρ_{10} — Ams decay and formation of X_S
ρ_{11} — Ams decay and formation of BAP
ρ_{12} — aerobic hydrolysis
ρ_{13} — anoxic hydrolisys
ρ_{14} — X_{STO} decay

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