Model-based comparison of sequencing batch reactors and continuous-flow activated sludge processes for biological wastewater treatment

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Abstract

This study compares, based on mathematical modelling, continuous-flow activated sludge processes (CAS) and sequencing batch reactors (SBR). The steady-state or periodic steady-state of CAS and SBR processes is compared for a feed composed of readily or slowly biodegradable substrates, for carbon and for carbon and nitrogen removal. The simulations are carried out for different values of the SRT (solids residence time), HRT (hydraulic residence time), number of cycles and internal recycle. If the SRT is large enough, the SBR can remove the influent biodegradable COD completely, while the CAS has a residual effluent COD concentration. For carbon and nitrogen removal, the SBR can remove the ammonia completely while the CAS has a residual effluent ammonia concentration. For typical values of the operating parameters, the CAS gives higher total nitrogen removal than the SBR, which becomes comparable to the CAS only for a large number of cycles per day.

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Nomenclature

Name	Description	Unit
AerFill	Aerobic fill phase (SBR)	
AnoxFill	Anoxic fill phase (SBR)	
b	Kinetic parameter (endogenous metabolism, heterotrophic biomass)	d^{-1}
b_A	Kinetic parameter (endogenous metabolism, autotrophic biomass)	d^{-1}
BOD_5	Biochemical oxygen demand (5 days)	kg/m^3
CAS	Continuous-flow activated sludge process	
COD	Chemical oxygen demand	kg/m^3
Eff	Effluent withdrawal phase (SBR)	
HRT	Hydraulic residence time	d
HRT_1	HRT for anoxic reactor (CAS, carbon and nitrogen removal)	
HRT_2	HRT for aerobic reactor (CAS, carbon and nitrogen removal)	
K_S	Kinetic parameter (readily biodegradable substrate)	$kg\ COD/m^3$
K_X	Kinetic parameter (slowly biodegradable substrate)	$kg\ COD/kg$
k_h	Kinetic parameter (slowly biodegradable substrate)	$kg\ COD/kg/d$
K_{SNO3}	Kinetic parameter (anoxic growth of heterotrophic biomass)	$kg\ N\text{-}NO_3/m^3$
K_{SNH3}	Kinetic parameter (growth of autotrophic biomass)	$kg\ N\text{-}NH_3/m^3$
NH_3	Ammonia concentration	$kg\ N\text{-}NH_3/m^3$
NH_{30}	NH_3 in feed stream	$kg\ N\text{-}NH_3/m^3$
NH_{31}	NH_3 in anoxic reactor (CAS, carbon and nitrogen removal)	$kg\ N\text{-}NH_3/m^3$
NH_{32}	NH_3 in aerobic reactor (CAS, carbon and nitrogen removal)	$kg\ N\text{-}NH_3/m^3$
NO_3	Nitrate concentration	$kg\ N\text{-}NO_3/m^3$
NO_{31}	NO_3 in anoxic reactor (CAS, carbon and nitrogen removal)	$kg\ N\text{-}NO_3/m^3$
NO_{32}	NO_3 in aerobic reactor (CAS, carbon and nitrogen removal)	$kg\ N\text{-}NO_3/m^3$
NO_{3Aer}	NO_3 at the end of the aerobic phase (SBR, carbon and nitrogen removal)	$kg\ N\text{-}NO_3/m^3$
NO_{3Anox}	NO_3 at the end of the anoxic phase (SBR, carbon and nitrogen removal)	$kg\ N\text{-}NO_3/m^3$
No cycles	Number of cycles per day	d^{-1}
P_X	Sludge production flow rate	kg/d
Q	Influent flow rate	m^3/d
Q_{fill}	Influent flow rate during the filling phase (SBR)	m^3/d
Q_R	Sludge recycle flow rate	m^3/d
Q_I	Internal recycle flow rate	m^3/d
Q_W	Sludge withdrawal flow rate	m^3/d
Q_{With}	Sludge withdrawal flow rate during the sludge withdrawal phase (SBR)	m^3/d
$Q_{O2biomass}$	Oxygen consumption by the microorganisms (total)	kg/d
$Q_{O2biomass,het}$	Oxygen consumption by the heterotrophic biomass	kg/d
$Q_{O2biomass,aut}$	Oxygen consumption by the autotrophic biomass	kg/d
R	Sludge recycle ratio	dimensionless
R_I	Internal recycle ratio	dimensionless
r_{hydr}	Hydrolysis rate of the slowly biodegradable substrate	$kg\ COD/m^3/d$
r_{XAer}	Growth rate of heterotrophic biomass (aerobic)	$kg/m^3/d$
r_{XAnox}	Growth rate of heterotrophic biomass (anoxic)	$kg/m^3/d$
r_{endAer}	Endogenous metabolism rate of heterotrophic biomass (aerobic)	$kg/m^3/d$
$r_{endAnox}$	Endogenous metabolism rate of heterotrophic biomass (anoxic)	$kg/m^3/d$
r_{endA}	Endogenous metabolism rate of autotrophic biomass	$kg/m^3/d$
r_{SAer}	Organic substrate removal rate (aerobic)	$kg\ COD/m^3/d$
r_{SAnox}	Organic substrate removal rate (anoxic)	$kg\ COD/m^3/d$
r_{NH3Aer}	Ammonia removal rate (aerobic)	$kg\ N\text{-}NH_3/m^3/d$
$r_{NH3Anox}$	Ammonia removal rate (anoxic)	$kg\ N\text{-}NH_3/m^3/d$
r_{NO3Aer}	Nitrate removal rate (aerobic)	$kg\ N\text{-}NO_3/m^3/d$
$r_{NO3Anox}$	Nitrate removal rate (anoxic)	$kg\ N\text{-}NO_3/m^3/d$
S	Readily biodegradable substrate concentration	$kg\ COD/m^3$
S_0	S in feed stream	$kg\ COD/m^3$
S_1	S in anoxic reactor (CAS, carbon and nitrogen removal)	$kg\ COD/m^3$

Symbol	Description	Units
S_2	S in aerobic reactor (CAS, carbon and nitrogen removal)	kg COD/m³
SBR	Sequencing batch reactor	
SRT	Solids residence time	d
$t_{Aerfill}$	Length of the aerobic filling phase	d
$t_{Aerreact}$	Length of the aerobic reaction phase	d
$t_{Anoxfill}$	Length of the anoxic filling phase	d
$t_{Anoxreact}$	Length of the anoxic reaction phase	d
t_{cycle}	Length of the entire cycle	d
t_{eff}	Length of the effluent withdrawal phase	d
t_{settle}	Length of the settling phase	d
t_w	Length of the sludge withdrawal phase	d
V	Reactor volume	m³
V_{full}	Volume of the SBR when full	m³
V_1	V of anoxic reactor (CAS, carbon and nitrogen removal)	m³
V_2	V of aerobic reactor (CAS, carbon and nitrogen removal)	m³
W	Sludge withdrawal phase (SBR)	
X	Heterotrophic biomass concentration	kg/m³
X_R	X at the bottom of the settling tank (CAS)	kg/m³
X_1	X in in anoxic reactor (CAS, carbon and nitrogen removal)	kg/m³
X_2	X in in aerobic reactor (CAS, carbon and nitrogen removal)	kg/m³
X_A	Autotrophic biomass concentration	kg/m³
X_{A1}	X_A in in anoxic reactor (CAS, carbon and nitrogen removal)	kg/m³
X_{A2}	X_A in in aerobic reactor (CAS, carbon and nitrogen removal)	kg/m³
X_{AR}	X_A at the bottom of the settling tank (CAS)	kg/m³
X_S	Slowly biodegradable substrate concentration	kg COD/m³
X_{S0}	X_S in feed stream	kg COD/m³
$Y_{X/S}$	Yield of heterotrophic biomass on COD	kg/kg COD
$Y_{XA/NO3}$	Yield of autotrophic biomass on nitrate	kg/kg N-NO_3
μ_{max}	Kinetic parameter (aerobic and anoxic growth of heterotrophic biomass)	d^{-1}
μ_{maxA}	Kinetic parameter (growth of autotrophic biomass)	d^{-1}

1. Introduction

Biological wastewater treatment is used globally to process large volumes of municipal and industrial wastewaters, with the aim of reducing the concentration of organic matter and in some cases of nitrogen before the treated wastewaters can be safely discharged into the environment. Aerobic processes are the most common for biological wastewater treatment processes and are very energy intensive, due to the energy requirements for aeration, which account for 47-70 % of the total energy consumption of the process (Daverey et al., 2019). It is estimated that 3 % of the electrical energy consumption in the US is due to biological wastewater treatment processes (McCarty et al., 2011). In the design of biological wastewater treatment processes, it is important to choose the process configuration and the operating parameters that maximise the removal of the organic matter and, if required, nitrogen and minimise energy consumption.

The continuous-flow activated sludge process (CAS) and the sequencing batch reactor (SBR) are common process configurations for biological wastewater treatment (Henze et al., 2008), based on suspended-growth open mixed cultures. The CAS is the most common process and consists, in its simplest configuration, of a biological reactor followed by a settling tank, which generates concentrated microorganisms for recycling to the reactor and for withdrawal and a clarified effluent stream. The SBR is one of the alternatives to the CAS and is characterised by a sequence of phases in the same vessel. In its simplest configuration, the SBR consists of a fill phase, followed by a reaction phase, sludge withdrawal, settling and effluent withdrawal. After the clarified effluent is withdrawn, a new cycle is started with a new fill.

Although the CAS process has been in use for approximately 100 years and the SBR for several decades and they have been the subject of many published papers, little

theoretical or experimental study has been published on the comparison of the performance (e.g. COD and nitrogen removal, oxygen consumption) of these processes. Understanding the differences between the CAS and the SBR and the effect of operating parameters on their performance is important in order to choose the most suitable configuration and to achieve the desired treatment efficiency with the minimum energy consumption. Mirbagheri et al. (2017) compared the performance of CAS, SBR and other process configurations at pilot scale for a municipal wastewater and found that SBR gave a higher BOD_5 removal than the CAS. Wanner (1992) found similar performance for SBR and CAS processes for COD and nitrogen removal for a municipal wastewater. Papadimitrou et al. (2009) compared SBR and CAS processes for the treatment of an industrial wastewater, obtaining higher removal of COD and BOD_5 in the SBR.

The limitation of the cited and of other experimental studies on the comparison of SBR and CAS is that those findings are only valid for the particular wastewater and process conditions which were investigated. To fill this gap, this study is aimed at a theoretical comparison of the CAS and the SBR, identifying the expected analogies and differences in the performance of these processes for different operating parameters and process scenarios. The comparison is based on kinetic models of biological wastewater treatment and on the solution of steady-state mass balances, using, for the SBR, the method we developed for the calculation of the periodic steady state (Dionisi et al., 2016). SBR and CAS are compared for the processes for carbon removal and for carbon and nitrogen removal. The CAS and SBR are compared for their removal of carbon and nitrogen, for oxygen consumption and sludge production, providing insight into how to choose the best process configuration and how to optimise process performance.

2. Methodology

2.1 Process configurations

The process configurations considered in this study for the CAS and SBR are shown in Figures 1 and 2, respectively. In all cases, the biological reactors are assumed to be completely mixed and the settling process is assumed to be perfect, with no microorganisms leaving with the clarified effluent. We assume that no reactions occur during settling. All species, except the microorganisms, are assumed to be soluble and their concentration is assumed not to change in the settling process.

The CAS for carbon removal (Figure 1a) is modelled as a continuous-flow process with a completely-mixed reactor followed by a settling tank. In the biological reactor, heterotrophic microorganisms remove the organic substrate. The settling tank separates the microorganisms, which are partly recycled and partly withdrawn. The CAS for carbon and nitrogen removal (Figure 1b) is modelled as a sequence of two reactors, anoxic and aerobic, followed by settling tank. In the anoxic reactor the heterotrophic microorganisms remove the organic substrate using nitrate as electron acceptor. In the aerobic reactor, the heterotrophic microorganisms remove the residual organic matter and the autotrophic microorganisms convert ammonia into nitrate. Nitrate is recycled back into the anoxic reactor via the internal recycle. The processes occurring in the SBR are the same as in the CAS. The SBR is modelled as a sequence of phases. The cycle of the SBR for carbon removal (Figure 2a) starts with the fill phase, followed by the reaction phase and by the sludge withdrawal phase (fill, reaction and sludge withdrawal are aerated and mixed). After sludge withdrawal, the settling phase separates the microorganisms from the soluble species. At the end of the settling phase, the effluent is withdrawn and a new

cycle starts with a new fill. The SBR for carbon and nitrogen removal has a similar cycle pattern as the SBR for carbon removal, but the reaction phase is split into anoxic and aerobic phases. Similarly to the corresponding CAS process, the fill for the SBR for carbon and nitrogen removal occurs under anoxic conditions.

The carbon removal processes (SBR and CAS) were simulated in two scenarios with a feed composed of only readily biodegradable and of only slowly biodegradable substrates. The carbon and nitrogen removal processes were only simulated with a feed composed of readily biodegradable substrates.

The values of the operating parameters used in the base case for the SBR and CAS are shown in Table 1.

2.2 Kinetic models

The reaction kinetics considered in this study are the same for the CAS and the SBR and are reported below. Equations (1)-(13) represent a model with microorganisms growth and endogenous metabolism and are typical reaction rates used for biological wastewater treatment processes. We assume that endogenous metabolism converts microorganisms into carbon dioxide and water, with no generation of inerts. The values of the parameters used in this study are reported in Table 2 and are typical values for these processes. Equations (1)-(13), their derivations and the values used for the parameters can be found in the literature (Henze et al., 2000; Dionisi, 2017). We assumed that the limiting substrates are: COD for the aerobic metabolism of heterotrophic microorganisms; COD and nitrate for the anoxic metabolism of heterotrophic microorganisms; ammonia for the aerobic metabolism of autotrophic microorganisms. We assumed that oxygen is in excess in aerobic conditions and is not present in anoxic conditions.

$$r_{\text{XAer}} = \mu_{\max} \frac{S}{K_S + S} X \tag{1}$$

$$r_{\text{endAer}} = -b\, X \tag{2}$$

$$r_{\text{XAnox}} = \mu_{\max} \frac{S}{K_S + S} \frac{NO_3}{K_{SNO_3} + NO_3} X \tag{3}$$

$$r_{\text{endAnox}} = -b\, \frac{NO_3}{K_{SNO_3} + NO_3} X \tag{4}$$

$$r_{\text{XA}} = \mu_{\text{maxA}} \frac{NH_3}{K_{SNH_3} + NH_3} X_A \tag{5}$$

$$r_{\text{endA}} = -b_A X_A \tag{6}$$

$$r_{\text{hydr}} = -k_h \frac{X_S/X}{K_X + X_S/X} X \tag{7}$$

$$r_{SAer} = -\frac{r_{\text{XAer}}}{Y_{X/S}} \tag{8}$$

$$r_{SAnox} = -\frac{r_{\text{XAnox}}}{Y_{X/S}} \tag{9}$$

$$r_{NH3Anox} = -(r_{XAnox} + r_{endAnox}) \cdot 0.12 \tag{10}$$

$$r_{NH3Aer} = -r_{XA}\left(0.12 + \frac{1}{Y_{XA/NO3}}\right) - r_{endA} \cdot 0.12 - (r_{XAer} + r_{endAer}) \cdot 0.12 \tag{11}$$

$$r_{NO3Anox} = \frac{-r_{XAnox}\left(\frac{1}{Y_{X/S}} - 1.42\right) + 1.42 \cdot r_{endAnox}}{2.86} \tag{12}$$

$$r_{NO3Aer} = \frac{r_{XA}}{Y_{XA/NO3}} \tag{13}$$

2.3 Mass balances

The steady state values of the CAS were calculated by solving the steady state mass balances that describe the process. For the SBR, a periodic steady state was defined as the condition when the time profiles of all the variables during a cycle don't change between consecutive cycles. The periodic steady state for the SBR was calculated by solving the mass balances and imposing the condition that the initial and final value of each variable during the cycle are the same.

In this section, we summarise the mass balances which were solved for the various process configurations. Derivation and explanation of the equations and their solution methods (Microsoft Excel, Solver add-in) are shown in our previous work (Dionisi, 2017; Dionisi et al., 2016).

2.3.1 CAS, carbon removal with readily biodegradable substrate in the feed

In this configuration, the key operating parameters are the SRT and the HRT, which are expressed as:

$$SRT = \frac{VX}{Q_W X_R} \tag{14}$$

$$HRT = \frac{V}{Q} \tag{15}$$

The steady state mass balances are reported by Equations (16)-(18).

Heterotrophic microorganisms in the reactor:

$$\frac{(r_{XAer}+r_{endAer})}{X} + \frac{RX_R}{X \cdot HRT} = \frac{(1+R)}{HRT} \tag{16}$$

Organic substrate in the reactor:

$$\frac{(S_0-S)}{X \cdot HRT} = \frac{-r_{SAer}}{X} \tag{17}$$

Heterotrophic microorganisms in the whole system (reactor+settling tank):

$$\frac{(r_{XAer}+r_{endAer})}{X} = \frac{1}{SRT} \tag{18}$$

The steady state values for S, X and X_R were calculated by solving Equations (16)-(18) for given values of SRT, HRT and R. After the solutions of Equations (16)-(18), the oxygen consumption by the microorganisms and the sludge production were calculated from Equations (19) and (20):

$$\frac{Q_{O2biomass}}{Q} = (S_0 - S) - \frac{X \cdot HRT}{SRT} \cdot 1.42 \tag{19}$$

$$\frac{P_X}{Q} = \frac{HRT \cdot X}{SRT} \tag{20}$$

2.3.2 CAS, carbon removal with slowly biodegradable substrate in the feed

The definition of SRT and HRT are still given by Equations (14) and (15). The steady state mass balances for heterotrophic microorganisms in the reactor and in the whole system are still given by Equations (16) and (18). The mass balances for the slowly and readily biodegradable substrate in the reactor are given by Equations (21) and (22), respectively.

$$\frac{(X_{S0} - X_S)}{X \cdot HRT} = \frac{r_{\text{hydr}}}{X} \tag{21}$$

$$\frac{(S_0 - S)}{X \cdot HRT} + \frac{r_{\text{hydr}}}{X} = \frac{-r_{SAer}}{X} \tag{22}$$

The steady state for this process was calculated by solving Equations (16), (18), (21), (22) for the variables, X_S, S, X and X_R for given values of SRT, HRT and R. The oxygen consumption and sludge production were still calculated from Equations (19) and (20).

2.3.3 CAS, carbon and nitrogen removal

In this configuration the SRT is defined as:

$$SRT = \frac{V_1(X_1 + X_{A1}) + V_2(X_2 + X_{A2})}{Q_W(X_R + X_{AR})} \tag{23}$$

There are two values for the HRT, HRT_1 and HRT_2, referred to reactor 1 and 2, respectively:

$$HRT_1 = \frac{V_1}{Q} \tag{24}$$

$$HRT_2 = \frac{V_2}{Q} \tag{25}$$

The process is characterised by the mass balances (26)-(37).

Heterotrophic biomass in reactor 1:

$$\frac{(r_{XAnox}+r_{endAnox})}{X_1} + \frac{RX_R}{X_1 HRT_1} + \frac{R_I X_2}{X_1 HRT_1} = \frac{(1+R+R_I)}{HRT_1} \tag{26}$$

Autotrophic biomass in reactor 1:

$$\frac{RX_{AR}}{X_{A1}HRT_1} + \frac{R_I X_{A2}}{X_{A1}HRT_1} = \frac{(1+R+R_I)}{HRT_1} \tag{27}$$

Heterotrophic biomass in reactor 2:

$$\frac{(r_{X2}+r_{end2})}{X_2} + \frac{(1+R+R_I)X_1}{X_2 HRT_2} = \frac{(1+R+R_I)}{HRT_2} \tag{28}$$

Autotrophic biomass in reactor 2:

$$\frac{(r_{XA2}+r_{endA2})}{X_{A2}} + \frac{(1+R+R_I)X_{A1}}{X_{A2}HRT_2} = \frac{(1+R+R_I)}{HRT_2} \tag{29}$$

Heterotrophic biomass in the whole system:

$$\frac{(r_{X1}+r_{end1})}{X_1} + (r_{X2}+r_{end2})\frac{HRT_2}{X_1 HRT_1} = \frac{X_R}{X_1 HRT_1}\left(\frac{HRT_1(X_1+X_{A1})+HRT_2(X_{A2}+X_2)}{SRT(X_R+X_{AR})}\right) \tag{30}$$

Autotrophic biomass in the whole system:

$$\frac{(r_{XA2}+r_{endA2})}{X_{A2}} = \frac{X_{AR}}{X_{A2}HRT_2}\left(\frac{HRT_1(X_1+X_{A1})+HRT_2(X_{A2}+X_2)}{SRT(X_R+X_{AR})}\right) \tag{31}$$

Carbon substrate in reactor 1:

$$\frac{S_0+RS_2+R_I S_2}{X_1 HRT_1} = \frac{(-r_{SAnox})}{X_1} + \frac{(1+R+R_I)S_1}{X_1 HRT_1} \tag{32}$$

Carbon substrate in reactor 2:

$$\frac{(1+R+R_I)S_1}{X_2 HRT_2} = \frac{(-r_{SAer})}{X_2} + \frac{(1+R+R_I)S_2}{X_2 HRT_2} \tag{33}$$

Ammonia in reactor 1:

$$\frac{r_{NH3Anox}}{X_1} + \frac{NH_{30}+RNH_{32}+R_I NH_{32}}{X_1 HRT_1} = \frac{(1+R+R_I)NH_{31}}{X_1 HRT_1} \tag{34}$$

Ammonia in reactor 2:

$$\frac{r_{NH3Aer}}{X_{A2}} + \frac{(1+R+R_I)NH_{31}}{X_{A2}HRT_2} = \frac{(1+R+R_I)NH_{32}}{X_{A2}HRT_2} \tag{35}$$

Nitrate in reactor 1:

$$\frac{RNO_{32} + R_I NO_{32}}{X_1 HRT_1} = \frac{r_{NO3Anox}}{X_1} + \frac{(1+R+R_I)NO_{31}}{X_1 HRT_1} \qquad (36)$$

Nitrate in reactor 2:

$$\frac{r_{NO3Aer}}{X_{A2}} + \frac{(1+R+R_I)NO_{31}}{X_{A2} HRT_2} = \frac{(1+R+R_I)NO_{32}}{X_{A2} HRT_2} \qquad (37)$$

The steady state of the process was calculated by solving Equations (26)-(37) for the variables S_1, S_2, X_1, X_2, X_{A1}, X_{A2}, NH_{31}, NH_{32}, NO_{31}, NO_{32}, X_R, X_{AR} for given values of SRT, HRT_1, HRT_2, R and R_I. Once Equations (26)-(37) were solved, the sludge production and oxygen consumption were calculated from equations (38)-(41).

$$P_X = \frac{HRT \cdot (X_R + X_{AR})}{SRT} \qquad (38)$$

$$Q_{O2biomass} = Q_{O2biomass,het} + Q_{O2biomass,aut} \qquad (39)$$

$$\frac{Q_{O2biomass,het}}{Q} = (S_0 - S) - \frac{HRT \cdot X_R}{SRT} \cdot 1.42 - [(R_I + R)NO_{32} - (1 + R + R_I)NO_{31}] \cdot 2.86 \qquad (40)$$

$$\frac{Q_{O2biomass,aut}}{Q} = \left(4.57 - 1.42 Y_{XA/NO3}\right)(NO_{32} - NO_{31})(1 + R + R_I) + \frac{b_A X_{A2} 1.42}{HRT_2} \qquad (41)$$

The total nitrogen removal was calculated from Equation (42):

$$Total\ nitrogen\ removal = \left(\frac{NH_{30} - (NO_{32} + NH_{32})}{NH_{30}}\right) \cdot 100 \qquad (42)$$

2.3.4 SBR, carbon removal with readily biodegradable substrates in the feed

The key design parameters are the HRT and SRT which are expressed as follows:

$$SRT = \frac{V_{full}}{Q_{With} t_W Nocycles} \qquad (43)$$

$$HRT = \frac{V_{full}}{Q_{fill} t_{fill} Nocycles} \qquad (44)$$

The mass balances of biomass, substrate and reactor volume are shown in Equations (45)-(47). In the mass balances for the SBR, we used the notation $f(x)\big|_{Name\ of\ the\ phase(s)}$ to mean that the function f(x) is non zero only during the specified phase(s) and equal to 0 during the rest of the cycle (Dionisi et al., 2016).

Biomass (at the periodic steady state):

$$\int_{cycle}\left[\left(r_{XAer}+r_{endAer}\right)\big|_{AerFill,AerReact,W}-\frac{X}{V/V_{full}}\frac{1}{HRT\cdot t_{Aerfill}Nocycles}\bigg|_{AerFill}+\right.$$

$$\left.\frac{X}{V/V_{full}}\frac{1}{Nocycles\cdot t_{eff}}\left(\frac{1}{HRT}-\frac{1}{SRT}\right)\bigg|_{W}\right]dt=0 \tag{45}$$

Substrate (at the periodic steady state):

$$\int_{cycle}\left[r_{SAer}\big|_{AerFill,AerReact,W}+\frac{1}{HRT\cdot t_{Aerfill}\cdot Nocycles}\frac{(S_0-S)}{V/V_{full}}\bigg|_{AerFill}\right]dt=0 \tag{46}$$

Reactor volume:

$$\frac{d\left(V/V_{full}\right)}{dt}=\frac{1}{HRT\cdot t_{Aerfill}Nocycles}\bigg|_{AerFill}-\frac{1}{Nocycles\cdot t_{eff}}\left(\frac{1}{HRT}-\frac{1}{SRT}\right)\bigg|_{Eff}-\frac{1}{SRT\cdot t_W\cdot Nocycles}\bigg|_{W} \tag{47}$$

The periodic steady state was calculated from the solutions of Equations (45)-(47). For given values of the length of the phases, Nocycles, HRT and SRT, the solution of Equations (45)-(47) gave the profiles of S(t), X(t) and V/V$_{full}$(t) at the periodic steady state. After the solution of Equations (45)-(47), the sludge production and oxygen consumption were calculated from Equations (19) and (20), using the calculated value of X at the end of the sludge withdrawal phase.

2.3.5 SBR, carbon removal with slowly biodegradable substrates in the feed

The SRT and HRT are still defined by Equations (43) and (44) and the mass balance for biomass by Equation (45). The balance for the reactor volume is given by Equation (47). The balances for the slowly and readily biodegradable substrates are given by Equations (48) and (49).

Slowly biodegradable substrate (at the periodic steady state):

$$\int_{cycle} \left[r_{hydr}\big|_{AerFill,AerReact,W} + \frac{1}{HRT \cdot t_{Aerfill} \cdot Nocycles} \frac{(X_{S0}-X_S)}{V/V_{full}}\bigg|_{AerFill} \right] dt = 0 \qquad (48)$$

Readily biodegradable substrate (at the periodic steady state):

$$\int_{cycle} \left[(r_S - r_{hydr})\big|_{AerFill,AerReact,W} - \frac{1}{HRT \cdot t_{Aerfill} \cdot Nocycles} \frac{S}{V/V_{full}}\bigg|_{AerFill} \right] dt = 0 \qquad (49)$$

The solution of Equations (45), (47)-(49) gave the profiles of S(t), X(t) and V/V$_{full}$(t) at the periodic steady state. The sludge production and oxygen consumption were calculated from Equations (19) and (20).

2.3.6 SBR, carbon and nitrogen removal

The SRT and HRT are still expressed by Equations (43) and (44). The mass balances are expressed by Equations (50)-(54).

Substrate (at the periodic steady state):

$$\int_{cycle} \left[\begin{matrix} r_{SAnox}|_{AnoxFill,AnoxReact} + r_{SAer}|_{AerReact,W} \\ + \frac{1}{HRT \cdot t_{Anoxfill} \cdot Nocycles} \frac{(S_0-S)}{V/V_{full}}\bigg|_{AnoxFill} \end{matrix} \right] dt = 0 \qquad (50)$$

Heterotrophic biomass (at the periodic steady state):

$$\int_{cycle} \left[\begin{matrix} (r_{XAnox} + r_{endAnox})|_{AnoxFill,AnoxReact} + (r_{XAer} + r_{endAer})|_{AerReact,W} \\ -\frac{X}{V/V_{full}} \frac{1}{HRT \cdot t_{Anoxfill} Nocycles}\bigg|_{AnoxFill} + \frac{X}{V/V_{full}} \frac{1}{Nocycles \cdot t_{eff}} \left(\frac{1}{HRT} - \frac{1}{SRT}\right)\bigg|_{Eff} \end{matrix} \right] dt = 0 \quad (51)$$

Autotrophic biomass (at the periodic steady state):

$$\int_{cycle} \left[\begin{matrix} (r_{XA} + r_{endA})|_{AerReact,W} - \frac{X_A}{V/V_{full}} \frac{1}{HRT \cdot t_{Anoxfill} Nocycles}\bigg|_{AnoxFill} + \\ \frac{X_A}{V/V_{full}} \frac{1}{Nocycles \cdot t_{eff}} \left(\frac{1}{HRT} - \frac{1}{SRT}\right)\bigg|_{Eff} \end{matrix} \right] dt = 0 \qquad (52)$$

Ammonia (at the periodic steady state):

$$\int_{cycle} \left[\begin{array}{l} r_{NH3Anox}|_{AnoxFill,AnoxReact} + r_{NH3Aer}|_{AerReact,W} \\ + \dfrac{1}{HRT \cdot t_{Anoxfill} \cdot Nocycles} \dfrac{(NH_{30} - NH_3)}{V/V_{full}} \Big|_{AnoxFill} \end{array} \right] dt = 0 \tag{53}$$

Nitrate (at the periodic steady state):

$$\int_{cycle} \left[\begin{array}{l} r_{NO3Anox}|_{AnoxFill,AnoxReact} \\ + r_{NO3Aer}|_{AerReact} + \dfrac{1}{HRT \cdot t_{Anoxfill} \cdot Nocycles} \dfrac{-NO_3}{V/V_{full}} \Big|_{AnoxFill} \end{array} \right] dt = 0 \tag{54}$$

The periodic steady state was calculated by solving Equations (50)-(54) and (47), obtaining the profiles of S(t), X(t), X$_A$(t), NH$_3$(t), NO$_3$(t) and V/V$_{full}$(t). The production of microorganisms was calculated from Equation (55) and the oxygen consumption from Equations (39), (56) and (57).

$$\frac{P_X}{Q} = \frac{HRT \cdot (X + X_A)}{SRT} \tag{55}$$

$$\frac{Q_{O2biomass,het}}{Q} = (S_0 - S) - \left(\frac{HRT}{SRT}\right) X \, 1.42 - \left(\left(HRT - \frac{1}{No\ cycles}\right) NO_{3Aer} - HRT \cdot$$

$$NO_{3Anox} \right) No\ cycles \, 2.86 \tag{56}$$

$$\frac{Q_{O2biomass,aut}}{Q} = HRT\,(NO_{3Aer} - NO_{3Anox})\,No\ cycles \left(4.57 - 1.42\,Y_{\frac{XA}{NO_3}}\right) + (b_A\,X_A\,HRT\,1.42) \tag{57}$$

The total nitrogen removal was calculated with Equation (42) using the concentrations in the feed and in the effluent.

3. Results and discussion

3.1 Carbon removal

Figure 3 shows the profiles of the effluent substrate in the CAS and SBR as a function of the SRT for the case with the influent substrate being readily biodegradable. The main difference between the CAS and the SBR is that in the former there is a residual substrate concentration in the effluent (although, with the parameters used in this study, this is very low, less than 1 mg COD/l), while in the latter the influent substrate is entirely removed. The reason for the difference in the residual substrate concentrations in the CAS and in the SBR is that the former is a completely-mixed continuous-flow process, while the latter, although is completely mixed, has intermittent feed. In the CAS, the mass balance for the biomass in the whole system, Equation (18), can be re-arranged as:

$$S = \frac{bK_S SRT + K_S}{(\mu_{max} - b)SRT - 1}$$ (58)

Equation (58) shows that for $SRT \to \infty$, $S \to S_{min} = \frac{bK_S}{(\mu_{max} - b)}$, so S will be >0 as long as b and K_S are >0. The physical reason for this behaviour is that if the substrate concentration in the CAS was lower than S_{min}, the net biomass growth rate $(\frac{\mu_{max}S}{K_S + S} - b)$ would become negative, and, since biomass is continuously removed from the process, it wouldn't be possible to maintain any biomass concentration in the system. Therefore, any substrate concentration lower than S_{min} are impossible to be achieved in a CAS. The configuration of the SBR is different from the CAS in that biomass is not removed continuously but only intermittently at the end of the cycle. In the SBR substrate removal continues even when the substrate concentration reaches the S_{min} for the CAS, because substrate removal can

proceed even when the net growth rate of the biomass is negative, as long as the biomass is not continuously removed from the system.

As the SRT decreases, the effluent substrate concentration in the CAS gradually increases until the minimum SRT is reached when no substrate removal occurs and the biomass concentration in the reactor becomes zero. In the SBR, the effluent substrate concentration remains equal to zero until it rises suddenly when the minimum SRT is reached, which corresponds to no substrate removal and no biomass concentration. Interestingly, the minimum SRT which corresponds to process failure is slightly higher for the SBR than for the CAS. For $SRT>SRT_{min}$, the biomass concentration in the CAS and in the SBR is essentially the same, as the vast majority of the influent substrate is removed in both processes. Similarly, the oxygen consumption and the biomass production are essentially the same for the CAS and SBR (Figure 3b). Oxygen consumption increases as the SRT increases because of the increased role of endogenous metabolism and, for the same reason, biomass production decreases.

The biomass concentration in CAS and SBR processes is expected to depend on the HRT, as well on the SRT (Dionisi, 2017). Figure 4 shows that the biomass concentration is the same for both processes in a wide range of HRT values.

The difference between the effluent substrate concentration in the CAS and in the SBR is larger when the influent substrate is slowly biodegradable (Figure 5). In this case the SBR achieves complete removal of X_S and S, while for the CAS the effluent concentration of X_S never goes below approximately 20 mg/l.

Very limited comparison has been reported in the literature on COD removal for the same wastewater in SBR and CAS processes. Dockhorn et al. (2001) compared COD removal

in SBR and continuous flow processes at 8 and 20 d SRT. At SRT 8 d the performance of SBR and CAS processes was virtually the same, while at SRT 20 d the COD removal by the SBR was slightly higher. Mirbagheri et al. (2017) compared the SBR, the CAS and other process configurations for the treatment of a municipal wastewater. Both the BOD and COD removal were higher in the SBR than in the CAS. The BOD removal in the SBR was 98-99 % in all the investigated conditions, while for the CAS was in the range 85-93 %. The COD removal was 94-95 % in the SBR while it was 89-94 % in the CAS. Even though the SRT in this study was not reported, and it was not specified whether it was the same in the CAS and SBR, these results are in qualitative agreement with our simulations. Indeed, the almost complete BOD removal observed in this experimental study agrees well with the complete removal of the biodegradable COD which we simulated for the SBR. It should be noted that, although in our study the simulated variable was the COD and not the BOD, we assumed that all the COD was biodegradable, and therefore it is reasonable to compare, at least qualitatively, our effluent COD with the effluent BOD of experimental studies with real wastewaters. With real wastewaters a fraction of the COD may not be biodegradable, and this may explain the incomplete removal of the COD in experimental studies. Mohan et al. (2005) compared SBR and CAS for the treatment of complex chemical effluents observing higher BOD (92 vs 67 %) and COD (66 vs 54 %) removal for the SBR. Although the conditions in the SBR and CAS were not identical (SRT was 10 d in the SBR and 12 d in the CAS, the HRT and the organic load rate were also different), these results are in qualitative agreement with our findings. Papadimitrou et al. (2009) compared a SBR and a CAS process for the treatment of a coke oven wastewater, obtaining higher removal of COD and BOD_5 in the SBR. In particular, the

effluent BOD$_5$ of the SBR was very close to zero, and significantly lower than in the CAS, in agreement with our simulations. Higher rate of COD removal in a lab-scale SBR than in the continuous-flow full scale plant was also observed for a tannery wastewater (Carucci et al., 1999). A survey of 14 SBR plants in Germany (Teichgräber, 2001) showed almost complete BOD$_5$ removal, in agreement with this and other studies.

3.2 Carbon and nitrogen removal

Figure 6 compares the CAS and SBR in the process for carbon and nitrogen removal. The concentrations of heterotrophic and autotrophic biomass are essentially the same in both processes (Figure 6a). Analogously to what was observed for the process for carbon removal, the CAS has a residual substrate concentration in the effluent even at high SRT, while substrate degradation is complete for the SBR (Figure 6b). The concentration of effluent ammonia has the same trend as the one of the carbon substrate (Figure 6c): ammonia is completely removed in the SBR while there is a residual, although low, ammonia concentration in the effluent of the CAS. This is due to the fact that ammonia is the substrate for the autotrophic microorganisms and so the same considerations on the need of a minimum substrate concentration already made for carbon removal (Section 3.1) also apply to the autotrophic microorganisms. In the process of carbon and nitrogen removal, an important difference between the CAS and the SBR is the effluent nitrate concentration (Figure 6d), which is, at least with the base case process parameters, higher for the SBR. The higher nitrate concentration in the SBR corresponds to a lower extent of nitrogen removal in this process (Figure 6e). The reason for the higher effluent nitrate concentration in the SBR than in the CAS lies in the different operational mode of these processes. In both processes, the effluent nitrate concentration is determined by

the ammonia concentration at the inlet of the aerobic reactor (for the CAS) or at the start of the aerobic phase (for the SBR). The ammonia concentration at the inlet of the aerobic reactor in the CAS is mainly determined by the sludge and internal recycle ratios, which dilute the ammonia concentration in the feed. In the SBR instead, there are no recycle streams and ammonia concentration at the start of the aerobic phase is mainly determined by the number of cycles per day and by the HRT, which have the effect of diluting the ammonia concentration in the feed. With the process parameters of the base cases in Figure 6 (R_I=R=1 for the CAS, Nocycles=4, HRT=0.3 d for the SBR), the dilution of ammonia in the feed is larger for the CAS than for the SBR, resulting in lower effluent nitrate and higher nitrogen removal for the CAS. Figures 6d and 6e also show a slight increase in the effluent nitrate and, correspondingly, a slight decrease in the nitrogen removal, for both processes as the SRT increases. This is due to the increased contribution of endogenous metabolism as the SRT increases. Endogenous metabolism causes a release of ammonia, which is then nitrified increasing the effluent nitrate concentration.

Figure 7 shows the effect of HRT on nitrogen removal. For the CAS, the HRT has no effect on nitrogen removal, because in this continuous-flow process the ammonia dilution, which is a key factor determining the effluent nitrate concentration, is determined by the ratio of the influent, sludge recycle and internal recycle flow rates (i.e. by the recycle ratios) and not by the volume of the reactors. For the SBR, on the other hand, the ratio between the influent flow rate and the reactor volume (i.e. the HRT) affects the dilution of the ammonia in the feed and, correspondingly, the effluent nitrate concentration and the nitrogen removal. Increasing the HRT corresponds to increasing the reactor volume per

unit of influent flow rate, therefore increasing the dilution of the influent ammonia. Higher dilutions of the influent ammonia give lower ammonia concentrations at the start of the aerobic phase and, correspondingly, lower nitrate concentrations in the effluent and higher nitrogen removal.

Figure 8 shows the effect of the number of cycles in the SBR and of the internal recycle in the CAS. These two parameters, although they are different, have the similar function, as far as nitrogen removal is concerned, of diluting the ammonia concentration in the feed. For the CAS, increasing the internal recycle decreases the effluent nitrate and therefore increases the nitrogen removal. For the SBR, increasing the number of cycles per day, at a constant HRT, decreases the ammonia concentration at the end of the feeding period, and therefore also at the start of the aerobic phase, because the same volume of feed is split between a larger number of cycles. The lower ammonia concentration in turn corresponds to a lower nitrate concentration and a higher nitrogen removal.

Figure 9 compares the oxygen consumption in the CAS and SBR, as a function of the SRT and of the internal recycle (for the CAS) or number of cycles per day (for the SBR). In all cases the oxygen consumption increases as the SRT increases because of the increased effect of endogenous metabolism (same effect already observed for carbon removal). Oxygen consumption is lower for higher values of the internal recycle for the CAS and for higher values of the number of cycles for the SBR. The reason for this effect is that oxygen consumption decreases as nitrogen removal increases, because part of the COD is oxidised by nitrate rather than by oxygen. In all cases the biomass production

as a function of the SRT for the conditions reported in Figure 9 is virtually the same, confirming what was observed for the process for carbon removal in Figure 3b.

Although many studies have been published on either SBR or CAS processes for nitrogen removal, comparison of the nitrogen removal of these processes for the same wastewater are very limited. Sun et al. (2019) compared ammonia and total nitrogen removal in anaerobic/anoxic/aerobic SBR and CAS processes. The SBR was operated with 4 cycles per day and the CAS with an internal recycle ratio of 1. They observed almost complete ammonia removal in both processes but, in qualitative agreement with the present study, observed higher total nitrogen removal in the CAS than in the SBR. Almost complete ammonia removal in SBR processes was reported in a number of experimental studies (e.g. Yalmaz et al., 2001; Andreottola et al., 2001), in agreement with the results of our simulations. The effect of the HRT (at a fixed number of cycles per day as in our simulations in Figure 7) on nitrogen removal in SBR was experimentally investigated by Klimiuk et al. (2005), who observed an increase in nitrogen removal as the HRT increased, in agreement with our study. As far as the effect of the number of SBR cycles per day is concerned, Artan et al. (2002) simulated, based on a mathematical model of the SBR, SBR performance for 4-6 cycles per day, observing, in agreement with our study, a decrease in total nitrogen removal as the number of cycles per day decreased.

3.3. General discussion and comparison of SBR and CAS processes

This study highlighted, based on mathematical modelling, similarities and differences between SBR and CAS processes. The results of this study are important for the initial stage of process design, when the type of biological process (SBR or CAS) is chosen and

22

As far as the similarities are concerned, for carbon removal processes the biomass concentration and oxygen consumption are expected to be virtually the same, for the same SRT. In both process configurations, by increasing the SRT the oxygen consumption increases and the biomass production decreases. Higher oxygen consumption corresponds to higher energy consumption and operating costs. If the produced biomass is used, as it is done frequently, in an anaerobic digestion process for methane production and energy recovery, lower biomass production translates into lower energy recovery. Therefore, in order to minimise the overall energy input into the process, both the CAS and the SBR processes should be operated with the shortest possible SRT that ensures the desired removal of the organic matter. Successful investigation of activated sludge process operated at short SRT has recently been reported (e.g. Ge et al., 2017).

One important advantage of SBR vs CAS processes is predicted to be the lower concentration of substrate (organic matter and/or ammonia) in the effluent. This effect is expected to be more important for slowly biodegradable substrates, i.e. for substrates which need to be hydrolysed before being metabolised by microorganisms. Since generally most of the COD in domestic sewage is slowly biodegradable (Ohron et al., 1999), our study indicates that the SBR can potentially have a significant impact in improving the quality of the effluent wastewaters. However, systematic experimental comparison of the removal of slowly biodegradable substrates in SBR and CAS processes is limited. Therefore, one recommendation from this study is to carry out a

systematic experimental investigation of COD removal in SBR and CAS processes, with model (readily and slowly biodegradable) substrates and with real wastewaters.

Another important difference between the SBR and the CAS is the extent of nitrogen removal. If SBR processes are operated, as it is quite typical, with relatively low number of cycles per day and relatively short HRT, the extent of nitrogen removal is expected to be lower than in CAS processes. To increase nitrogen removal in SBR while maintaining a low HRT (which is desirable to reduce the capital cost of the plant), the number of cycles per day should be increased. This however could make the cycle length too short to leave enough time for the settling phase. A careful optimisation of the operating parameters, to be verified experimentally, is required to maximise nitrogen removal in SBR processes.

Our analysis is based on the use of intrinsic kinetics and does not consider the effect of configuration design parameters, e.g. tank dimensions or type of mixing and aeration system, on the performance of the SBR and CAS processes. Configuration design parameters can affect the performance of biological processes, for example tank geometry and diffusers layout affect oxygen transfer in CAS processes (Karpinska and Bridgeman, 2016). However, our study assumes that processes are well designed, without any non-ideal mixing or mass transfer limitations, so that reactors can be modelled as perfectly mixed vessels and process performance is only determined by the microbial kinetics and by the SRT, HRT, internal recycle ratio and number of cycles per day.

It should be noted that the conclusions of this study depend on the mathematical model and on the kinetic parameters used. Alternative models are also possible. For example, while we assumed that endogenous metabolism converts microorganisms only to carbon

dioxide and water, Bahar and Ciggin (2016), found that 25 % of the biomass converted by endogenous metabolism is converted into inert suspended solids. Inclusion of inert formation from endogenous metabolism would have a small effect in the calculation of suspended solids by our models but wouldn't significantly change the results of our study. As far as nitrogen removal is concerned, we ignored any intermediates in ammonia oxidisation to nitrate and in nitrate reduction to molecular nitrogen. However, nitrogen oxides (N_2O and NO) are intermediate in these processes and in some conditions can be released in the outlet gas stream (Domingo-Felez and Smets, 2020). Inclusion of the formation of these intermediates into our model would give a more accurate estimation of nitrogen removal but wouldn't change the comparison of nitrogen removal in CAS and SBR significantly. As far as the effect of the model parameters is concerned, the model parameters are expected to influence the extent of the observed differences between SBR and CAS processes, but not the general conclusions of this study. For example, Figure 10 shows the effect of changing the kinetic parameters K_S (Figure 10a) or b (Figure 10b) on the effluent substrate concentration calculated for the SBR and CAS. K_S and b are the main parameters that affect the net rate of biomass growth and therefore the rate of substrate removal, and can vary in relatively large ranges (Dionisi, 2017). Figure 10 shows that the model result observed previously in Figure 3a, i.e. that the substrate is completely removed in the SBR while a residual effluent concentration is present in the CAS, is still valid even for a large variation of the parameters K_S and b. While the extent of the effluent substrate concentration in the CAS depends on the values of K_S and b, complete removal is observed for the SBR for all the parameter values considered here. It is however important to use the results of this study to guide experimental work on the

comparison of SBR and CAS. The experimental work will provide insight on which model describes the processes better and on the appropriate range for the model parameters.

In this study, the calculations were carried out with Microsoft Excel, a general-purpose software. The same calculations can also be carried out with specialised software for the simulation of biological wastewater treatment processes. The differences between our approach and the modelling approach used in most specialised simulators have been discussed in our previous paper (Dionisi et al., 2016): a key difference is that our method allows the direct calculation of the SBR profiles at the periodic steady state without the need of the calculation of the process dynamics during start-up. However, any specialised commercial software can be used to select, design and optimise SBR and CAS processes according to the methodology and to the findings of the present study.

4. Conclusions

Based on mathematical models of the processes, we have shown that the SBR has the advantage, over the CAS, to be able to achieve a complete degradation of the biodegradable COD. On the other hand, a residual concentration of biodegradable COD is predicted to be present in the effluent stream of the CAS, at higher concentration for a feed composed of slowly biodegradable substrates. For carbon removal processes, no significant differences between the SBR and the CAS are expected in oxygen consumption and sludge production, for the same operating parameters. In both processes, the net energy input can be minimised by optimising the SRT. For carbon and nitrogen removal processes, with typical values of the operating parameters, a higher nitrogen removal is expected in the CAS. For the SBR, nitrogen removal can be improved by increasing the HRT and/or increasing the number of cycles per day.

Overall, this study has identified the analogies and differences to be expected between CAS and SBR processes. All the main predictions of the model should be subject to experimental validation, as differences in process performance and in the magnitude of the expected effects could arise between simulations and real plants, due to uncertainties in the model structure and parameters and to the effect of configuration design parameters, which can cause non-ideal mixing and mass transfer limitations. It is expected that this analysis will stimulate experimental validation work and will be the basis for an informed choice of the type of process and for advanced process design.

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Table 1. Operating parameters for the base case of the simulations. For the simulations in which these values were changed, this is specified in the corresponding figures.

Parameters	CAS carbon removal	CAS carbon and nitrogen removal	SBR carbon removal	SBR carbon and nitrogen removal
R, dimensionless	1	1	-	-
R_I, dimensionless	-	1	-	-
HRT_1, d	-	0.15	-	-
HRT_2, d	-	0.15	-	-
HRT, d	0.3	-	0.3	0.3
No cycles, cycles/d	-	-	4	4
$t_{Aerfill}$, min	-	-	5	-
$t_{Aerreact}$, min	-	-	290	-
$t_{Anoxfill}$, min	-	-	-	5
$t_{Anoxreact}$, min	-	-	-	145
$t_{Aerreact}$, min	-	-	-	145
t_w, min	-	-	5	5
t_{settle}, min	-	-	45	45
t_{eff}, min	-	-	15	15
t_{cycle}, min	-	-	360	360

Table 2. Kinetic parameters used in this study (CAS and SBR).

Parameters	Carbon removal		Carbon and Nitrogen removal
	Readily biodegradable feed	Slowly biodegradable feed	Readily biodegradable feed
μ_{max}, d^{-1}	6	6	6
μ_{maxA}, d^{-1}	-	-	4
b, d^{-1}	0.1	0.1	0.1
b_A, d^{-1}	-	-	0.1
K_S, kg COD/m^3	0.005	0.005	0.005
k_h, kg COD/kg/d	-	3.0	-
K_X, kg COD/kg	-	0.02	-
K_{SNO3}, kg N-NO$_3$/m^3	-	-	0.003
K_{SNH3}, kg N-NH$_3$/m^3	-	-	0.003
$Y_{X/S}$, kg/kg COD	0.3	0.3	0.3
$Y_{XA/NO3}$, kg/kg N-NO$_3$	-	-	0.1
S_0, kg COD/m^3	0.5	0.5	-
X_{S0}, kg COD/m^3	-	-	0.5
NH_{30}, kg N-NH$_3$/m^3	-	-	0.06
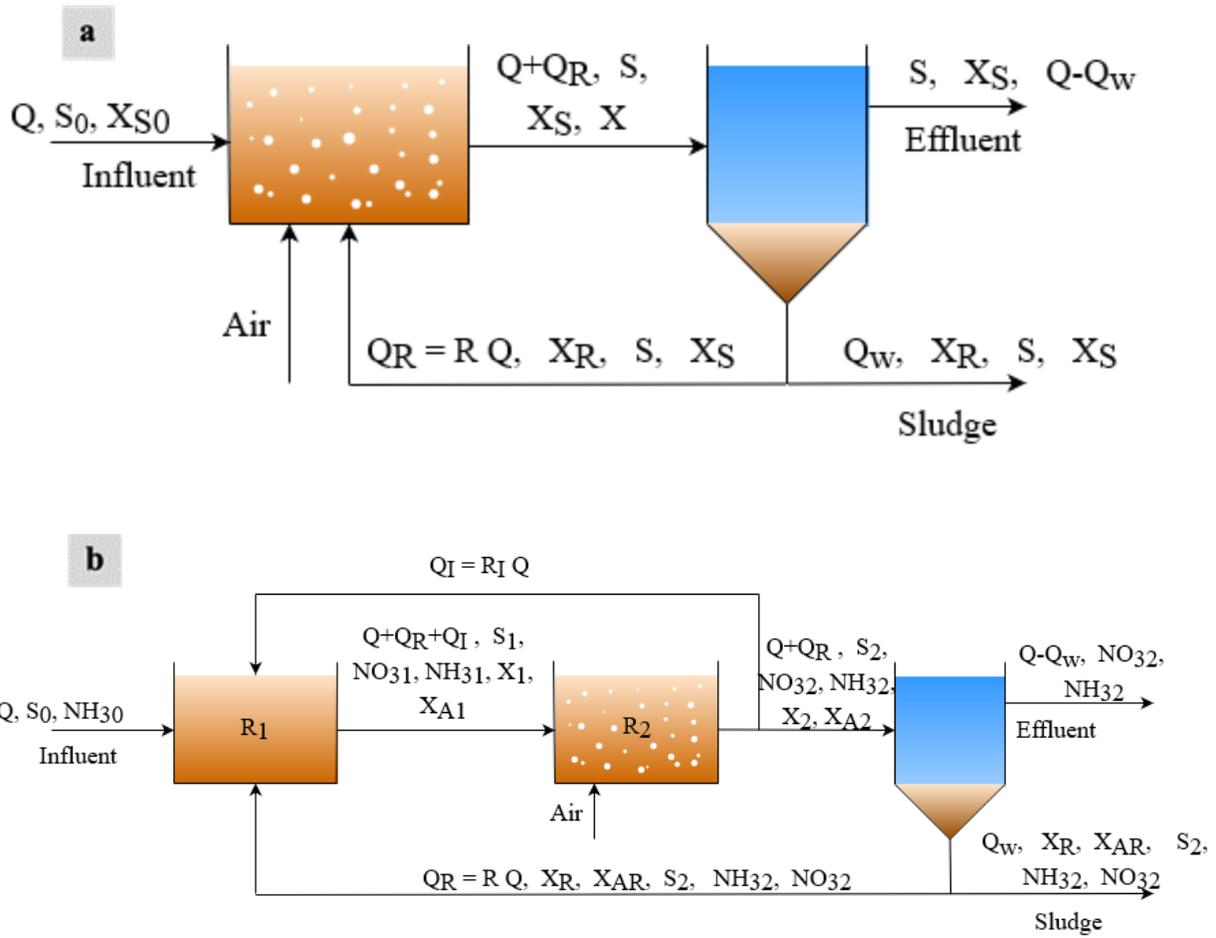
Figure 1. Configurations of the CAS: (a) Carbon removal; (b) Carbon and nitrogen removal.
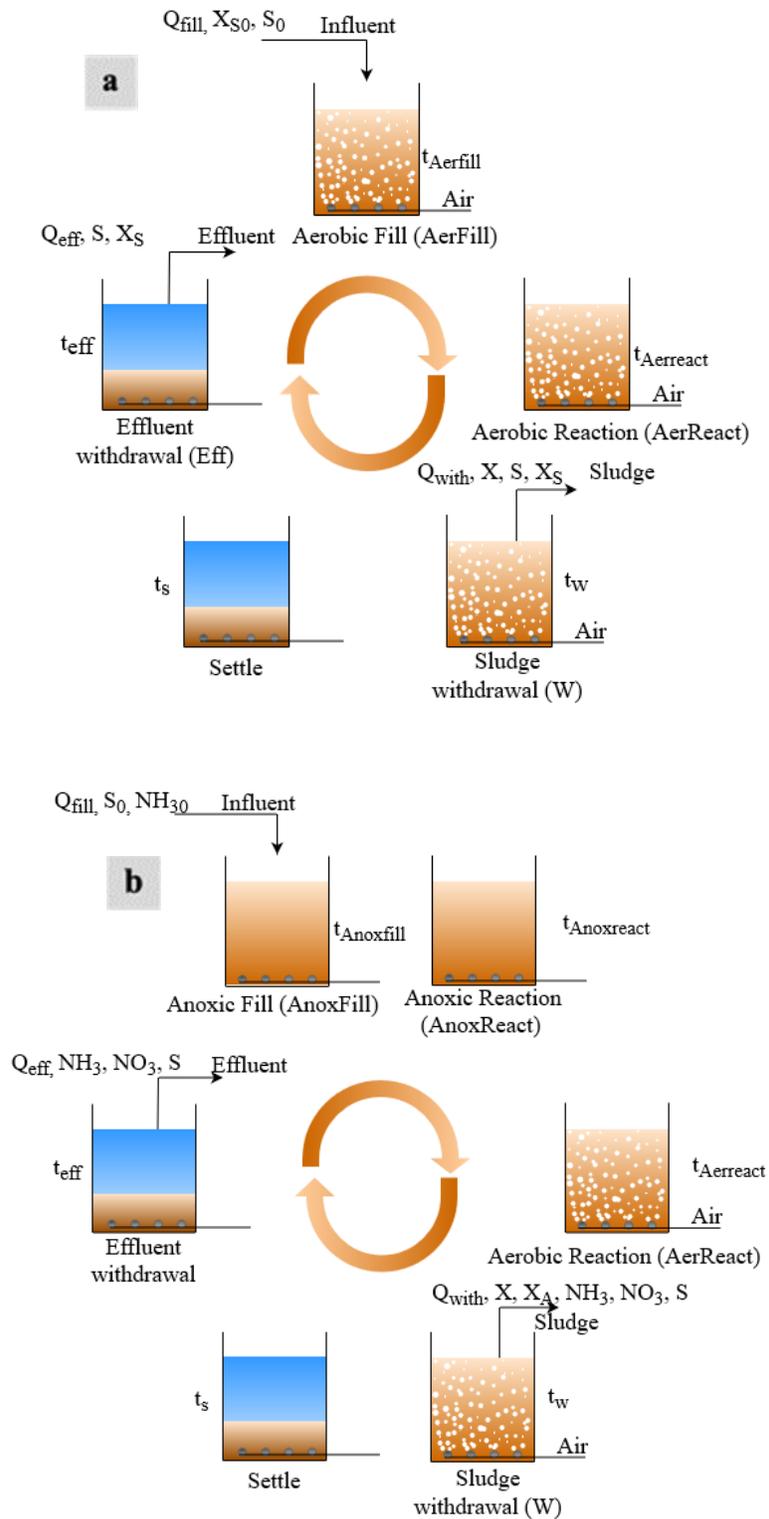
Figure 2. Configuration of the SBR: (a) Carbon removal; (b) Carbon and nitrogen removal.
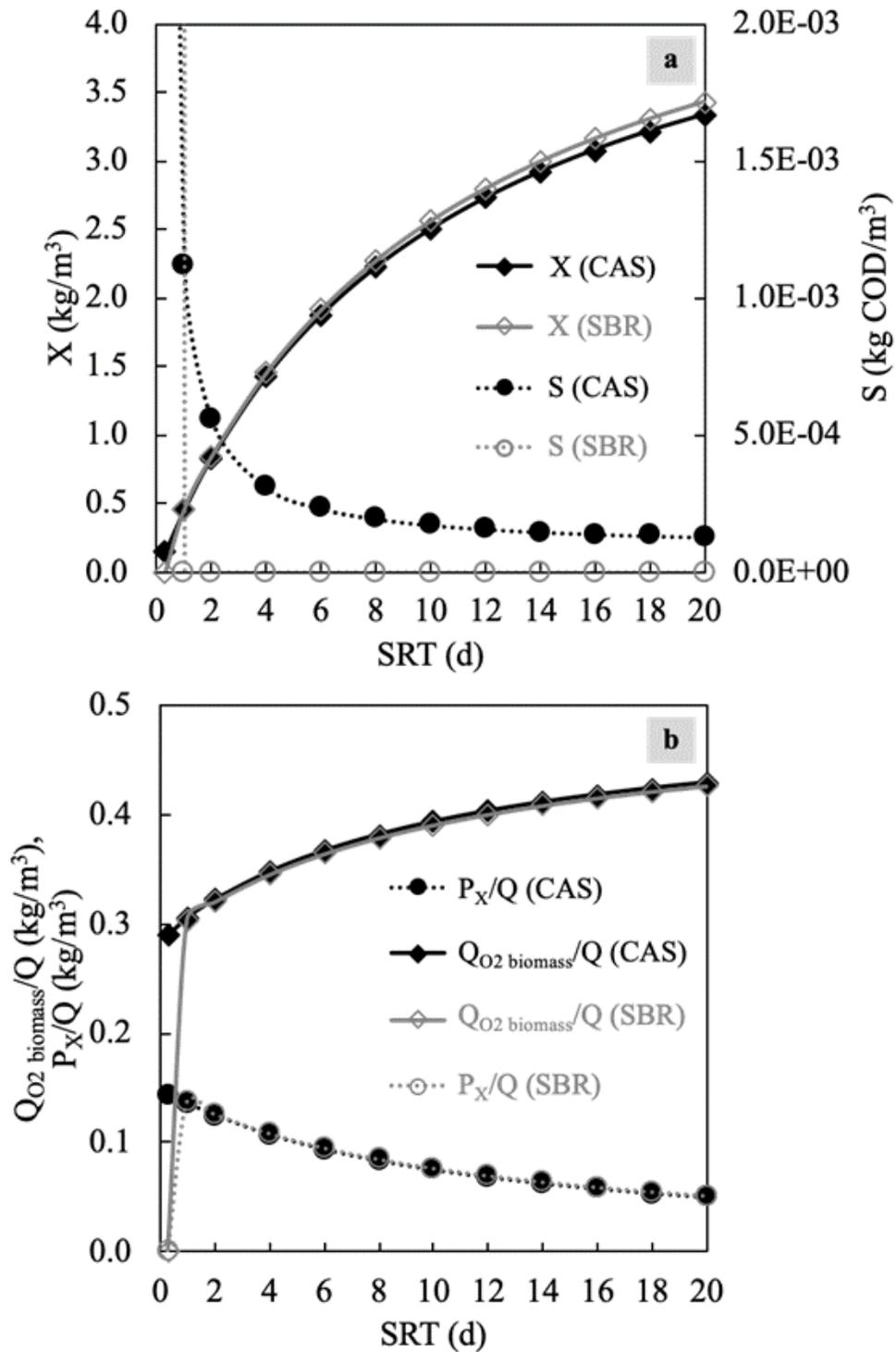
Figure 3. Effect of the SRT on (a) biomass (X) and substrate (S) concentrations and on (b) oxygen consumption ($Q_{O2biomass}/Q$) and sludge production (P_X/Q). Readily biodegradable substrate in the influent.
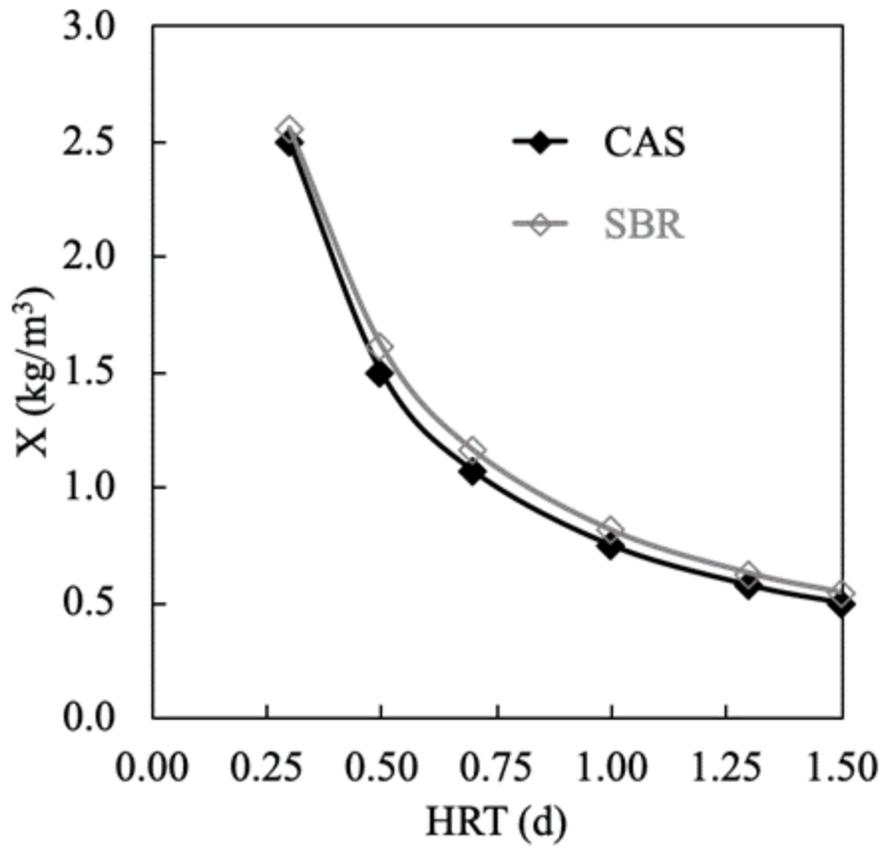
Figure 4. Effect of the HRT on the biomass concentration (X). Readily biodegradable substrate in the influent. SRT 10 d.
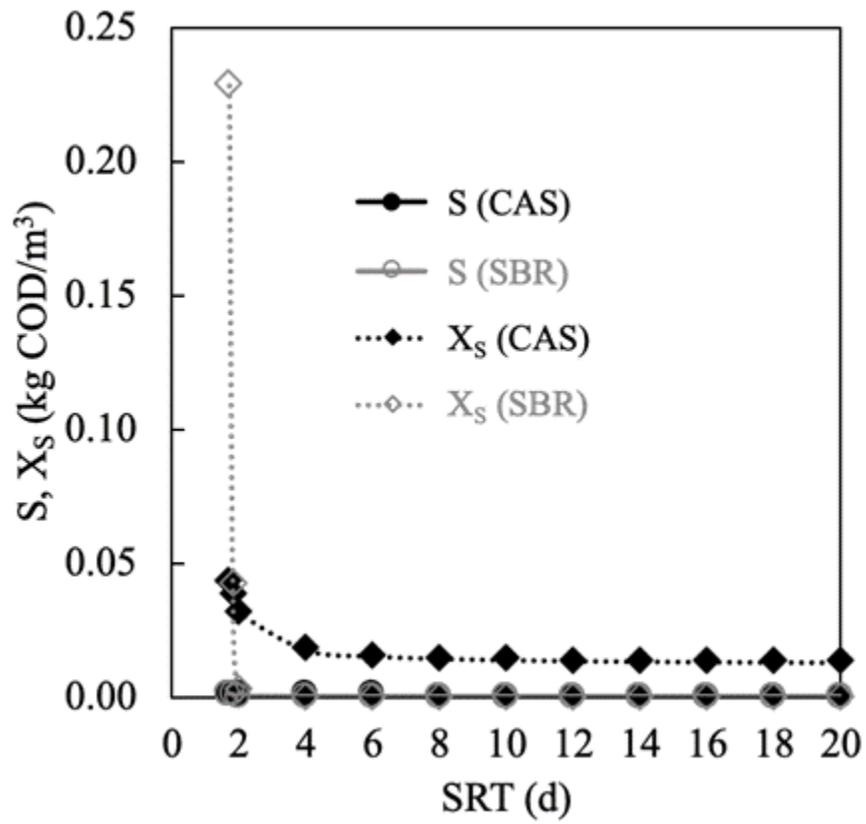
Figure 5. Effect of the SRT on the slowly (X_S) and readily (S) biodegradable substrate concentrations. Slowly biodegradable substrate in the influent.
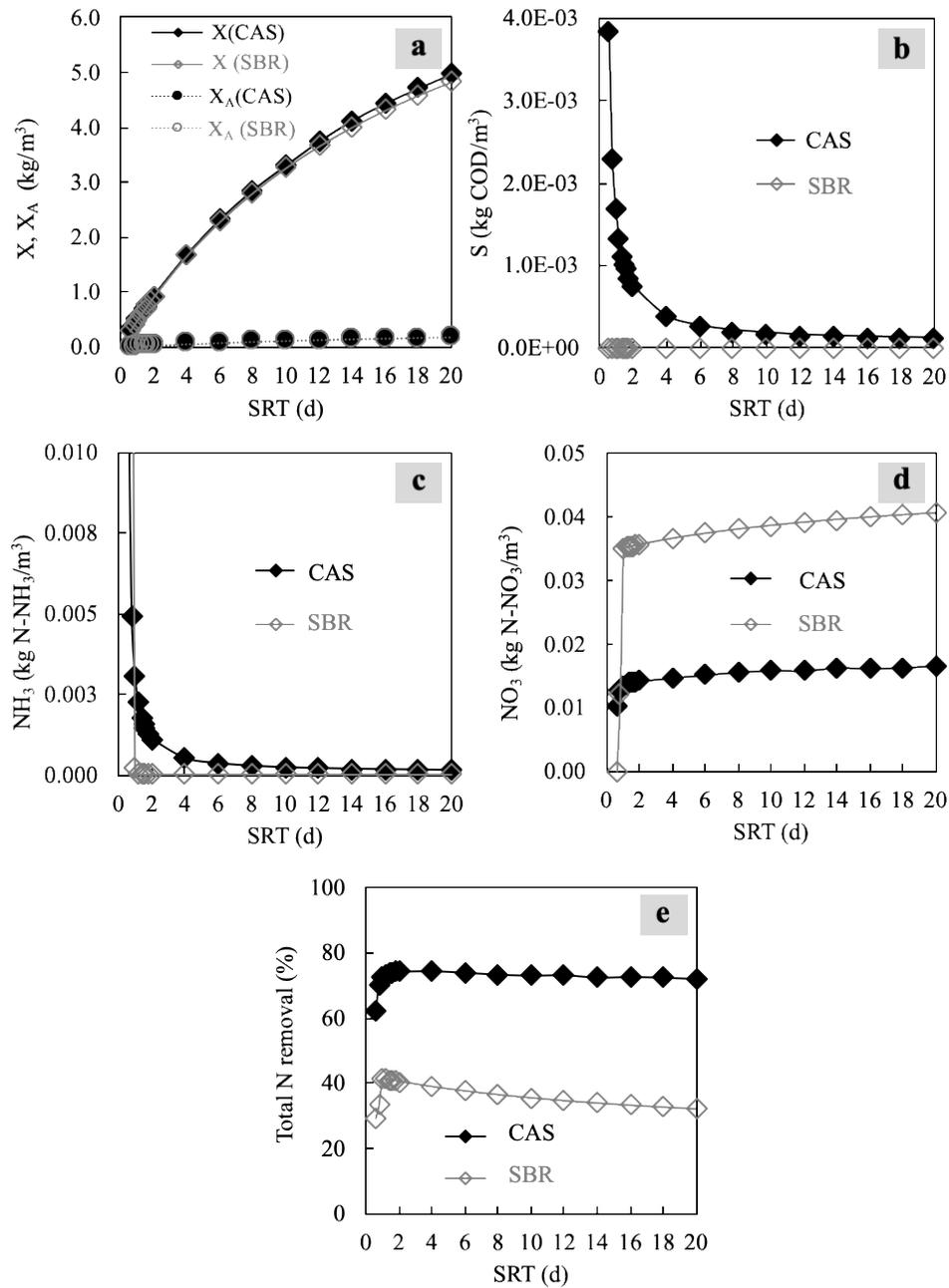
Figure 6. Effect of the SRT on the concentrations of (a) heterotrophic (X) and autotrophic (X_A) biomass, (b) substrate (S), (c) ammonia (NH_3), and (d) nitrate (NO_3) along with the effect on the (e) percentage of total nitrogen removed.
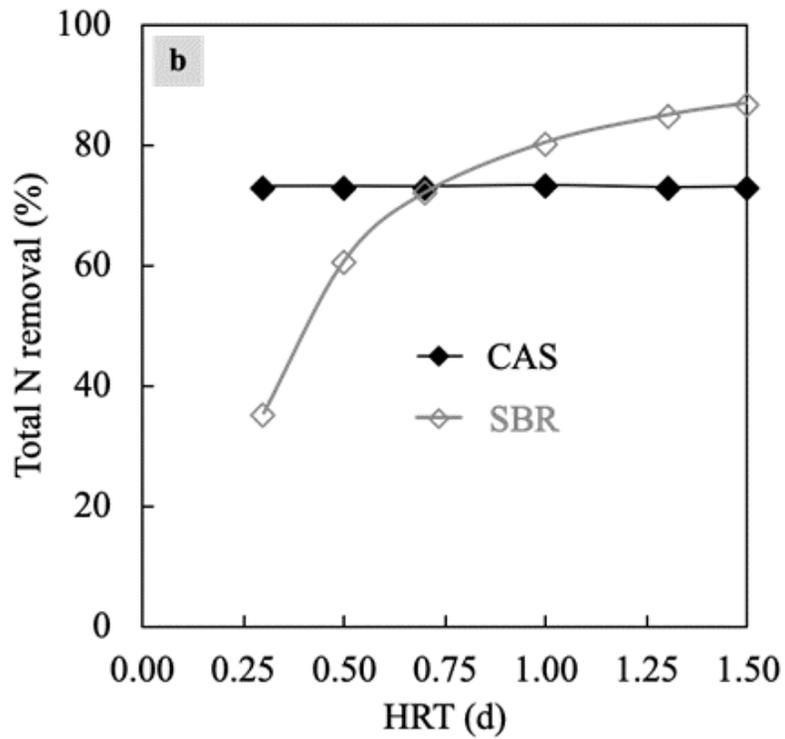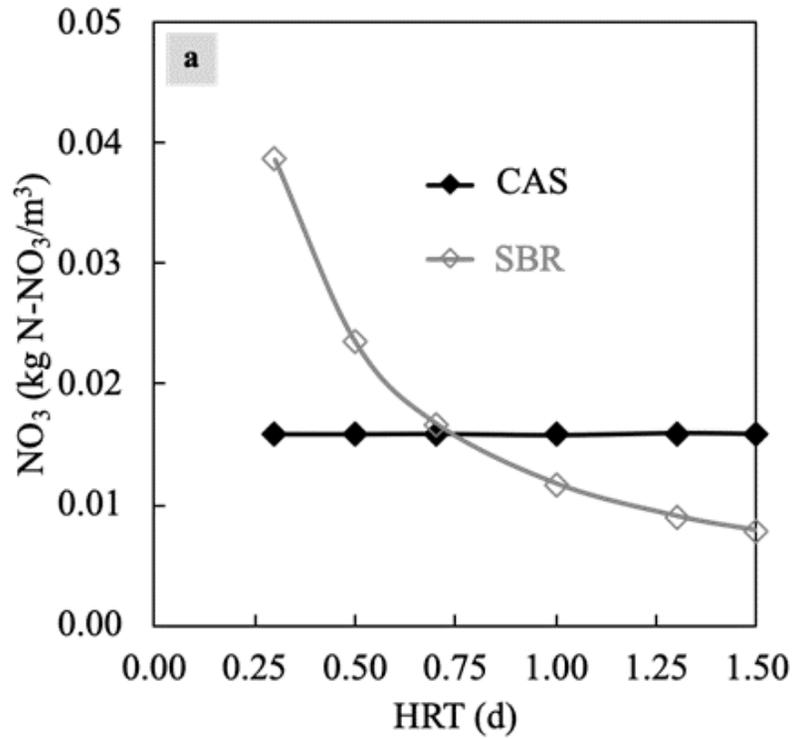
Figure 7. Effect of the HRT on the (a) concentration of nitrate (NO_3) and on the (b) percentage of total nitrogen removed. SRT 10 d.
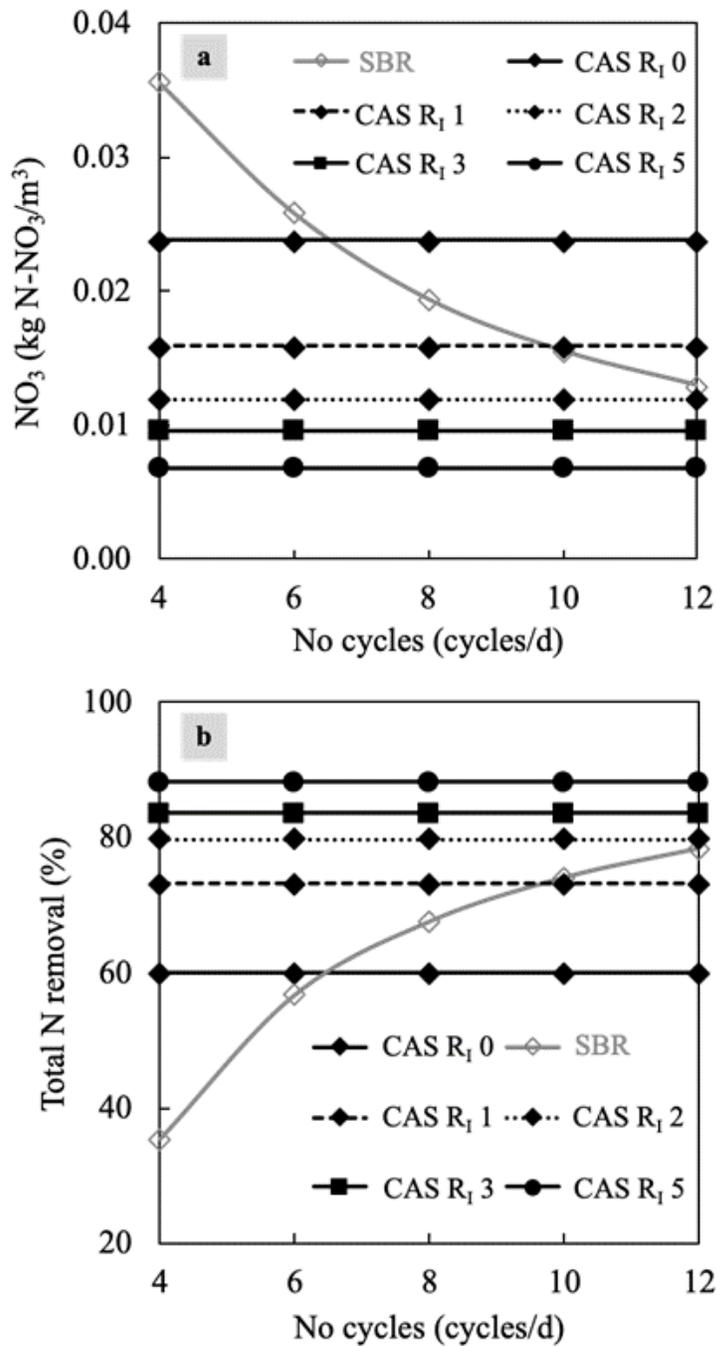
Figure 8. Effect of the number of cycles (No cycles) and the internal recycling rate (R_I) on the (a) nitrate concentration (NO_3) and on the (b) percentage of total nitrogen removed. SRT 10 d. In the SBR, changing the number of cycles per day was obtained by changing the length of all phases in the same proportion.
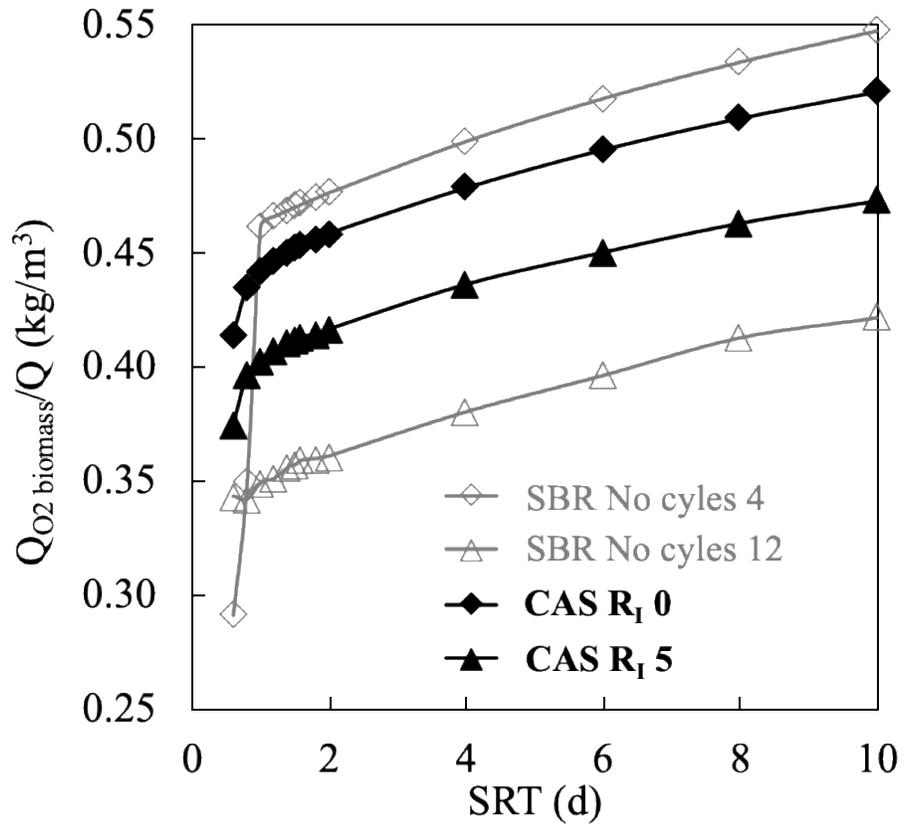
Figure 9. Oxygen consumption for the SBR and CAS for carbon and nitrogen removal.
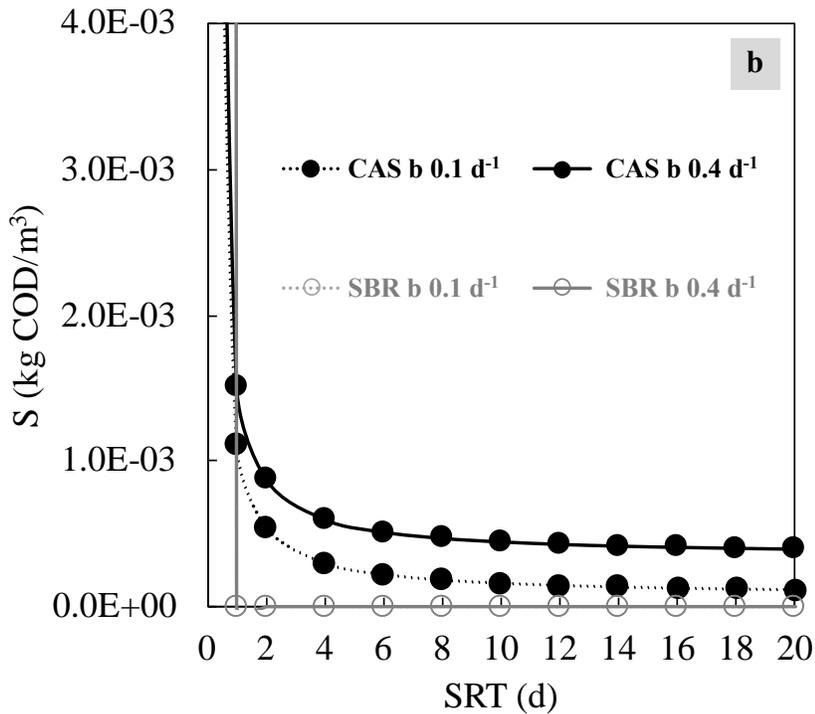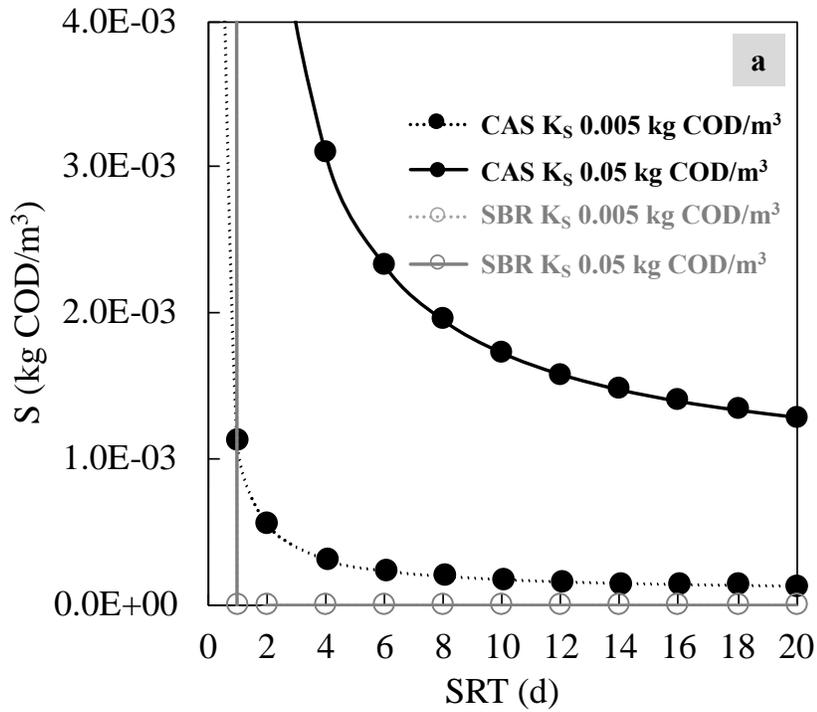
Figure 10. Effect of the value of the kinetic parameters (carbon removal, readily biodegradable feed). a) Effect of K_S (parameter in the Monod rate equation); b) effect of b (parameter in the endogenous metabolism rate equation). Other parameters have the values in Table 2.