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Minimum COD needs for denitrification: from biological models to experimental set-up

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ABSTRACT

The nitrogen content in treated wastewater is a key issue when considering discharge in sensitive areas or reuse targets as standards are getting increasingly stringent. In this study, a Membrane Biological Reactor (MBR), mainly dedicated to nitrogen removal through a nitrification-denitrification process was investigated in order to identify the minimum amount of organic matter that allows complete denitrification. Thus, the Minimum COD/N Ratio, referred to as MR, was assessed using activated sludge modeling (ASM3). Both lab-scale experiments and modeling results pointed out that endogenous denitrification could have a major role in nitrate removal. This role can be strengthened at high Solid Retention Times (SRT). Furthermore, the dissolved oxygen, provided by mixed liquor recirculation between aerobic and anoxic compartments, hindered the denitrification rate. An analytical expression for an apparent Minimum Ratio (MR_A) was developed, taking into account previously described processes. This allowed the influent COD to be adjusted to ensure complete denitrification. MR_A depends on main design characteristics and operating parameters, mainly the SRT, the anoxic compartment volume, the dissolved oxygen in the aerobic tank and the recirculation rate. For an SRT ranging from 40 to 60 d, laboratory experiments showed that, contrary to a COD/N ratio of 5, a value of 3.5 led to non-stable nitrate removal performances. This was consistent with the assessed MR_A, estimated at approximately 4, for identical operating conditions and design characteristics.

Keywords: MBR, ASM3, minimum COD/N ratio, endogenous denitrification, dissolved oxygen

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1. Introduction

Nitrogen is the second most abundant macro-pollutant present in domestic wastewater. An uncontrolled, unplanned or accidental release of a high nitrogen concentration could seriously disturb the ecological balance leading to excess nutrient enrichment problems [1,2]. Given the fact that nitrogen typically present in urban wastewater exists in soluble forms, its removal is very often achieved biologically by the Conventional Activated Sludge (CAS) process. However, WasteWater Treatment Plants (WWTP) using the CAS process have always suffered recurrent issues of biomass separation in the secondary clarifier which has led to the introduction of membrane technology in order to make the separation step more efficient and more reliable [3]. Over the last decade, membrane bioreactors (MBR) have become well established technology as an activated

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sludge process alternative for advanced municipal wastewater treatment [4]. The spread of MBR use is also due to other key features such as (i) high compactness, and thus a lower small footprint than the CAS process, (ii) higher Solid Retention Times (SRT) which increases the concentration of low growth rate microorganisms such as autotrophic bacteria [5] leading to an enhancement of nitrogen and refractory compounds removal [6–9], giving (iii) better water quality and allowing a possible direct reuse of treated effluents [10].

Although, nitrification performance is greatly improved in MBR, the denitrification rate is still strongly dependent on the amount of organic matter present in the anoxic tank. Thereby, the COD/N ratio is considered as a crucial parameter to achieve complete denitrification. It is also a determining criterion, as important as the SRT, which controls microbial diversity and growth [11,12]. Moreover, it has been demonstrated that working at low Organic Loading Rates (OLR) reduces Mixed Liquor Suspended Solid (MLSS) concentrations which decreases the propensity for membrane fouling, mixing problems and aeration inefficiency [13–15]. Thus, MBRs are facing a radical change to their operational management: an upstream Advanced Separation Process (ASP) could be used to extract organic matter more efficiently from the influent allowing the conversion of a greater part of the wastewater organic matter into biogas on the sludge line, which could cover MBR energy demand [16,17]. Hence, for the development of a positive energy wastewater treatment processes, the challenge is to operate the MBR at the lowest COD content. However, the COD/N ratio cannot drop below a certain value as denitrification needs organic matter in order to be successfully carried out. This critical value has to be determined to guarantee a total denitrification and, subsequently, the required effluent quality.

According to Verstraete and Philips, a minimum value of 3.5 for the COD/N ratio was calculated [18]. This value corresponds to the stoichiometric ratio required to achieve total nitrate reduction in nitrogen. But, in most cases, biological oxidation-reduction reactions have biomass yields (anabolism) that are below 1, since part of the substrate is degraded during catabolism. Few studies have tried to identify the needed minimum COD/N ratio. The proposed values have been estimated between 3 and 7 [19–25]. This wide range could be partly explained by differences in organic carbon sources or process design (recirculation/sequential aeration) [20,23,26–28]. Some authors recommended operating at values higher than 8 for the COD/N ratio in the influent to make sure that the requested denitrification rate is reached [29,30]. Moreover, none of the experimental studies reported in the literature were based on modeling approaches for assessing the Minimum COD/N Ratio (MR). Thus, the main objective of this work is to identify the MR and unfold its dependence on operating parameters using Activated Sludge Models (ASM).

2. Materials and methods

Experimental and modeling approaches were combined to review factors that influence nitrate and nitrite removal. The biological pathway described by the activated sludge model No. 3 (ASM3) was used [31], with a particular interest given to the COD/N ratio in order to find the lowest MR ensuring complete denitrification. An experimental investigation was conducted to check denitrification performances for the obtained MR. For this purpose, several experiments were performed on a laboratory scale MBR operating at low COD/N ratios. The organic carbon source was provided for the sole purpose of achieving complete denitrification. It is worth mentioning that, compared to conventional MBR treating effluents with higher organic matter input, the development of heterotrophic species, growing on organic matter, would be decreased, whereas the development of autotrophic species, consuming ammonia, would rather be increased.

2.1. Biological pathway according to ASM3

Activated sludge modeling is based on biological pathways, performed by heterotrophic and autotrophic biomass, on organic and nitrogen oxidation associated with an electron acceptor: Oxygen or Nitrate (Fig. 1). For this study, ASM3 was used with its standard notation [31].

All relationships between state variables are described in the Petersen matrix in Henze et al. study [31]. Fig. 1 shows the main processes involving heterotrophic biomass, that is, storage of biodegradable substrate (S_S), growth of heterotrophic biomass (X_H) and endogenous respiration of both heterotrophic biomass and storage products (X_{STO}) as well as their associated electron acceptor consumption.

I_e^- is the on/off switching function that allows shifting from aerobic conditions (oxygen electron acceptor) to anoxic conditions (nitrate electron acceptor). It is commonly expressed using Monod-type kinetics as they are widely accepted in modeling to demonstrate the effect of electron acceptor concentration on biological rates [31]. I_e^- is given by $\frac{S_{O_2}}{K_{O_2}+S_{O_2}}$ or $\frac{K_{O_2}}{K_{O_2}+S_{O_2}}$.

It should be noted that all the processes depicted in Fig. 1, occur at the expense of an electron acceptor, that is, oxygen (yellow arrows) or nitrate (green arrows). Thus, the endogenous respiration rate, involving electron acceptor consumption without exogenous substrate (S_s), is mainly due to (i) biomass decay and (ii) storage compound consumption. In aerobic conditions, the specific Oxygen Uptake Rate (OUR) for each bacterial population (heterotrophic or autotrophic) can be calculated using Eqs. (1) and (2):

$$\mathrm{OUR}_{\mathrm{endo,\,H}} = \left(1 - f_{\mathrm{XI}}\right) b_{\mathrm{H,O_2}} X_{\mathrm{H}} + b_{\mathrm{STO,O_2}} X_{\mathrm{STO}} \tag{1}$$

$$\mathrm{OUR}_{\mathrm{endo,\,A}} = \left(1 - f_{\mathrm{XI}}\right) b_{\mathrm{A,O_2}} X_{\mathrm{A}} \tag{2}$$

Since the electron acceptor is consumed during biomass decay, known also as endogenous respiration, the same process, in anoxic conditions, is called endogenous denitrification or endogenous Nitrate Uptake Rate ($\mathrm{NUR}_{\mathrm{endo}}$) [32]. The latter process could significantly contribute to the overall nitrate removal.

2.2. Experimental setup and analytical methods

A lab-scale MBR, equipped with two 30 L tanks in a serially positioned continuously stirred tank reactor was used

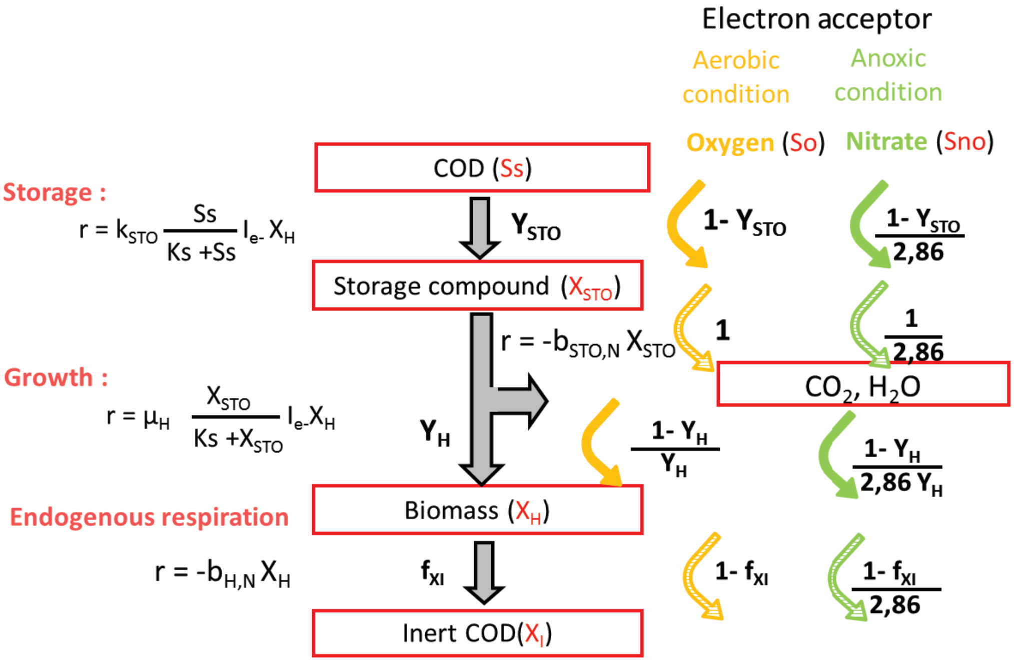

Fig. 1. ASM3 biological pathways (endogenous processes shown as hollow arrows).

for this study. The first tank was operating under anoxic conditions for nitrate removal (denitrification) and the second one was fully aerated in order to convert ammonia into nitrate (nitrification), as depicted in Fig. 2. The oxygen concentration in this tank was maintained at around 5 mg O_2/L. Then, to achieve the denitrification, the internal recirculation rate (*R* = Recirculation flow/Influent flow) of 4.6 was set from the aerated tank to the anoxic one. In this way, nitrate coming from the aerated tank was denitrified into N_2 gas in the anoxic tank where all the influent organic compounds were available and used to enhance the denitrification rate.

An ultrafiltration flat sheet membrane made of polyethersulfone, manufactured by Microdyn-Nadir® was immersed in the aerobic tank. Filtration was carried out under constant permeate flow rate, J_p, at 14.7 L/m²/h. The main operating conditions of the four experiments are presented in Table 1.

At the beginning of the first experiment, the reactor was inoculated with seeding sludge taken from a WWTP using the activated sludge process. The WWTP is operating with 5,000 population equivalent (p.e.) and at an SRT close to 20 d. The following experiments were carried out with the same sludge by changing operating conditions, namely SRT and OLR.

The synthetic influent was composed of a mixture of soluble biodegradable organic matter (sodium acetate and ethanol, 1:1) in addition to ammonium salts (ammonium chloride) with different COD/N ratios. Experiments were carried out at two COD/N ratios in the influent: 3.5 and 5, with a constant Nitrogen Loading Rate (NLR) of 0.161 kg N–NH4⁺/m³/d. The SRT effect was also investigated (Table 1). The Hydraulic Retention Time (HRT) was kept constant at a value of 12 h. All experiments were conducted at ambient temperature (18 ± 2°C) with a controlled pH (7.25 ± 0.25).

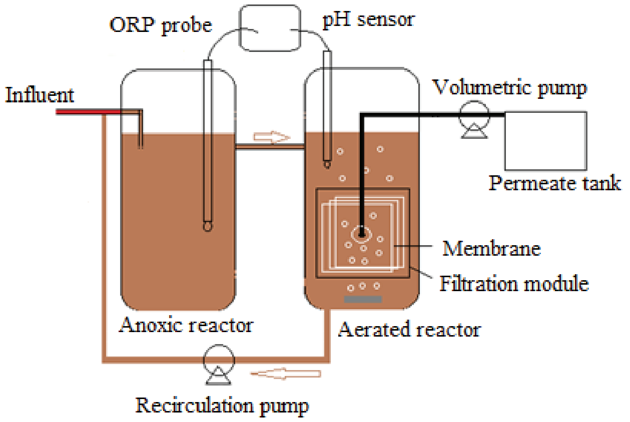

Fig. 2. Experimental laboratory scale MBR set-up.

Table 1
Operating conditions (HRT = 12 h, NLR = 0.161 kg N–NH_4^+/m³/d, J_p = 14.7 L/m²/h)

Experiment No.	Days of operation	SRT (d)	COD/N (–)	OLR (kg COD/m³/d)
1	D1–D37	40	5	0.805
2	D38–102	40	3.5	0.564
3	D103–198	60	3.5	0.564
4	D199–D254	60	5	0.805

Biological performances were followed up using various methods. The amounts of MLSS and Mixed Liquor Volatile Suspended Solids (MLVSS) were measured according to the standard methods [33]. Ammonium, nitrite and nitrate concentrations were assessed by means of LCK kits using a spectrophotometer (HACH DR/3,900). COD was analyzed by the AFNOR NFT 90–101 method using Hach COD kits. The Standard Deviation (*SD*) values given in Table 2 were calculated as follows:

$$SD = \sqrt{\frac{\sum\left(y_{\mathrm{i}} - \bar{y}\right)^2}{N}} \tag{3}$$

where y_i are the measured values, $\bar{y}$ is the mean value for each experiment and N is the number of steady state experimental points.

To measure biomass respirometric activities, activated sludge samples were put into sealed bottles where the Dissolved Oxygen (DO) was monitored using a DO sensor for the OUR calculation. OUR determination was always conducted under endogenous conditions [34–36]. These conditions were reached after 24 h of aeration without a substrate supply. Moreover, in order to differentiate autotrophic biomass activity from the heterotrophic one, specific inhibitors of autotrophs were employed. An allylthiourea (ATU) solution was added at a concentration of 10 mg/L for Nitrosomonas inhibition [37] and a sodium chlorate ($NaClO_3$) solution of 10 mmol/L was injected to inhibit Nitrobacter activity [38,39]. Thus, autotrophic and heterotrophic biomass concentrations were calculated based on analytical expressions of specific endogenous oxygen uptake rates, $OUR_{endo,H}$ and $OUR_{endo,A}$, previously developed in §2.1. Batch experiments in anoxic tanks at the same endogenous conditions were also performed to determine the endogenous nitrate uptake rate (NUR_{endo}), also called the endogenous denitrification rate.

3. Results and discussion

3.1. Experimental denitrification results

Nitrification and denitrification activities were monitored over the four experiments that lasted for more than 254 d of MBR operation. The nitrification rates were always maintained between 0.11 and 0.21 gN/gMLVSS/d, which are in the usual range found in the literature [40–42]. On the other hand, denitrification (i.e., nitrate or nitrite reduction) rates measured in the MBR were directly dependent on the COD/N ratio. In fact, at low COD/N ratios (Experiments 2 and 3), the lack of exogenous substrate leads to the presence of nitrate and nitrite in the anoxic tank.

Once the system's denitrification performances were stabilized, meaning that a steady state was reached, denitrification efficiency was evaluated through the amount of nitrite and nitrate that was still present in the anoxic compartment. Steady state values recorded during the four experiments are listed in Table 2.

The presence of nitrite and nitrate nitrogen (N-NOx) in the anoxic tank reflects incomplete denitrification. As shown in Table 2, for a COD/N ratio of 3.5 (experiments 2 and 3) and regardless of the SRT value, nitrate concentration exceeded 4 mg $N\text{-}NO_3^-$/L, with a very high value of nitrite (5–6 mg $N\text{-}NO_2^-$), which is another substantial indicator of a disturbed denitrification process. Nonetheless, much lower concentrations, less than 0.15 mg $N\text{-}NO_x$/L, were noticed during experiments 1 and 4. Therefore, no nitrites were accumulated in the anoxic tanks. The latter observations indicated that organic matter supply at a COD/N ratio equal to 5 was enough to ensure total and reliable denitrification with a SRT equal to 40 and 60 d.

On the basis of the preceding results, a COD/N ratio of 3.5 appeared to be insufficient and resulted in a partial denitrification. On the contrary, a COD/N ratio of 5 showed quite stable performances with a complete denitrification with no nitrite accumulation, meaning that, for the chosen MBR functioning parameters, the MR value lies between 3.5 and 5. On the other hand, varying the SRT, in the tested range from 40 to 60 d, did not seem to have a significant impact on improving or impeding denitrification for both considered ratios.

3.2. Theoretical MR assessment

3.2.1. Exogenous COD supply

According to the ASM3 matrix, the amount of nitrate nitrogen (N-NO3-) per COD consumned during exogenous denitrification is given by $Y_{STO,NOx}\left(1 - Y_{H,NOx}\right)/2.86$. Using parameter values proposed by Koch et al. [43], with YH,NOx and YSTO,NOx equal to 0.54 and 0.8 respectively, the COD/N ratio was calculated to be 7.77. However, this theoretical value is too high, as experimental evidence confirmed (part 3.1) complete denitrification occurring for a much lower ratio (COD/N of 5). Therefore, anoxic respiration on storage compounds (X_{STO}) could be assumed to be part of denitrification. As a result, $\left(1 - Y_{STO,NOx}Y_{H,NOx}\right)/2.86$ g $N\text{-}NO_3^-$ are denitrified per g COD, which leads to a

Table 2
Steady state nitrite and nitrate nitrogen measured concentrations in the anoxic tank (HRT = 12 h, NLR = 0.161 kg $N\text{–}NH_4^+/m^3/d$, J_p = 14.7 $L/m^2/h$)

Experiment No.	Operating conditions		MLVSS		Anoxic tank			
	SRT (d)	COD/N (–)	Concentration (g/L)	*SD* (–)	$N\text{-}NO_2^-$ (mg N/L)	*SD* (–)	$N\text{–}NO_3^-$ (mg N/L)	*SD* (–)
1	40	5	4.48	0.28	0.03	0.05	0.14	0.63
2	40	3.5	3.02	0.38	6.04	1.16	4.21	0.87
3	60	3.5	3.52	0.39	5.10	1.76	21.33	3.23
4	60	5	5.41	0.09	0.01	0.04	0.12	0.16

Table 3
Experimental and modeling endogenous denitrification rate values. (HRT = 12 h, NLR = 0.161 kg N–NH4$^+$/m^3/d, J_p = 14.7 L/m^2/h)

Experiment No.	Operating conditions		NUR_{endo} (mg N–NO_3/L/h)		
	SRT (d)	COD/N (–)	Experimental	ASM3	Error (%)
1	40	5	2.91	2.90	0.3
2	40	3.5	1.71	2.04	16.2
3	60	3.5	1.81	2.14	15.4
4	60	5	3.01	3.06	1.6

Minimum Exogenous COD/N Ratio (MR_{exo}) calculated as follows:

$$MR_{exo} = \frac{2.86}{1 - Y_{H,NO_x} Y_{STO,NO_x}} \tag{4}$$

Using the same values for $Y_{H,NOx}$ and $Y_{STO,NOx}$, MR_{exo} is equal to 5.04. Yet, compared to experimental data, this value is still high. Hence, other processes degrading nitrates should also be considered.

3.2.2. The influence of endogenous denitrification

Based on ASM3, under anoxic conditions two different denitrification processes occur simultaneously: exogenous and endogenous denitrification. During the first one, exogenous organic matter and cell material (X_{STO}) are oxidized whereas only cell materials are consumed in the second one. Thus, the exogenous denitrification rate is directly proportional to the OLR, contrary to the endogenous denitrification, whose rate is linked to the amount of cell materials (i.e., active biomass concentration) which is a function of OLR and SRT [32].

Endogenous denitrification contribution to nitrate removal could not be considered as negligible when the COD/N ratio is close to the rate-limiting value. Therefore, under low COD/N ratios, endogenous denitrification plays a significant role, in overall nitrate removal, and thus must be quantified. Consequently, MR should be determined by taking into account the contribution of endogenous denitrification as it is a process that takes place at the expense of nitrate consumption.

The utilization of nitrates due to anoxic endogenous respiration of active biomass (X_H, X_A) and storage products (X_{STO}) was accounted for as the so-called endogenous denitrification. In ASM3, its rate, NUR_{endo}, is explicitly expressed by:

$$NUR_{endo} = \frac{1 - f_{XI}}{2.86}\left(b_{H,NO_x} X_H + b_{A,NO_x} X_A\right) + \frac{1}{2.86} b_{STO,NO_x} X_{STO} \tag{5}$$

The previous expression can be simplified as autotrophic nitrate consumption is often negligible compared to the remaining processes:

$$NUR_{endo} = \frac{1}{2.86}\left[\left(1 - f_{XI}\right) b_{H,NO_x} X_H + b_{STO,NO_x} X_{STO}\right] \tag{6}$$

Eq. (6) reveals the direct relationship between NUR_{endo} and the heterotrophic biomass concentration (X_H). Storage products are closely linked to heterotrophic activity and so is their concentration (X_{STO}). To validate this expression, endogenous denitrification rates, calculated using Eq. (6), were compared to experimental measurements (Table 3).

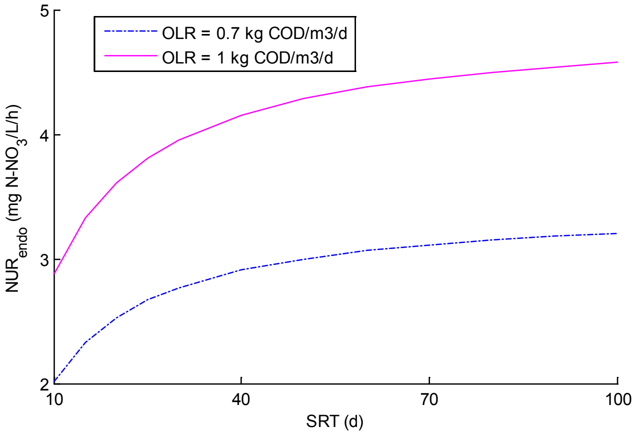

Fig. 3. Variation of endogenous denitrification rate with the OLR and the SRT.

From Table 3, an acceptable match between the experimental and the modeling results is obtained, despite some discrepancies, particularly for operation at a COD ratio of 3.5. So, the expression of the endogenous denitrification rate is validated and it can be employed to evaluate the MR with an error lower than 17% for a COD/N ratio between 3.5 and 5.

As mentioned above, according to Eq. (6), NURendo is proportional to heterotrophic biomass concentration which is strongly dependent on OLR and SRT (Monod-type kinetics). Simulations were run varying SRT for two OLR. The results are shown in Fig. 3. As predicted, NUR_{endo} rises with increasing OLR and SRT. For a given OLR value, NUR_{endo} reaches a pseudo plateau for a high SRT (> 40 d).

Ultimately, the MR can be calculated using the following equation:

$$MR = MR_{exo}\left[1 - NUR_{endo}\frac{a\,HRT}{S_{NOx}}\right] \tag{7}$$

where S_{NOx} is the nitrate nitrogen concentration (N-NO_3^-) present in the anoxic tank inlet, and a is the anoxic volume fraction defined as:

$$a = \frac{V_{anoxic\ volume}}{V_{total\ volume}} \tag{8}$$

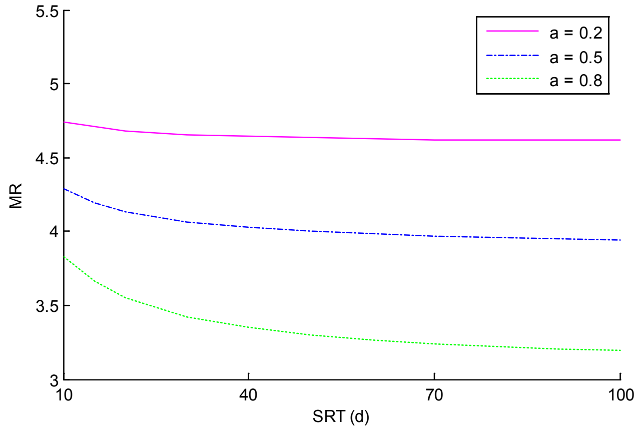

Fig. 4. Impact of the SRT and the anoxic volume fraction, a, on the MR.

Eq. (7) suggests that, in addition to the SRT, the MR depends on anoxic volume fraction, *a*, which is linked to the endogenous denitrification time. To better understand the impact of those two parameters, simulations based on Eq. (7) were performed and presented in Fig. 4.

The MR is inversely related to the SRT and to the anoxic volume fraction, since these latter are favorable to endogenous denitrification where no carbon source is required. The effect of anoxic volume fraction can be explained by the low rate of endogenous denitrification. Eq. (6) confirms this trend: higher anoxic tank volumes, leading to higher HRT in the anoxic volume, are needed to raise the contribution of endogenous denitrification contribution. Indeed, it can be noticed that, at low anoxic volume fractions ($a = 0.2$), the MR is almost independent of the SRT, which means that the contribution of endogenous denitrification to the overall denitrification process is meaningless. The opposite is observed for higher fractions ($a = 0.8$), where MR is more sensitive to SRT. As with the endogenous denitrification rate, a plateau is reached. Therefore, there is no significant MR decrease, that is, no considerable quantity of organic matter can be spared, above an SRT of 40 d.

3.2.3. The impact of DO on denitrification performance

Nitrogen removal involves separating aerobic and anoxic tanks and linking them with internal recirculation to enable optimal kinetic rates. Due to this appropriate design, nitrate concentration in the effluent is never zero and if the nitrification is complete the effluent nitrate concentration can be given by:

$$S_{NO_{x,e}} = \frac{1}{R+1} S_{NH_{4,i}} \tag{9}$$

where $S_{NH4,i}$ is ammonia concentration in the influent and $S_{NOx,e}$ is nitrate concentration in the effluent.

Consequently, only the recycled part of nitrate, which is denitrified (used as a final electron acceptor during the oxidation of organic carbon), must be taken into account in MR definition. Nonetheless, internal recirculation brings back mixed liquor which contains electron acceptors as well as dissolved oxygen with concentrations often above 4 mg O_2/L. When the recirculation rate is quite high, a lot of oxygen enters the anoxic tank. This leads to a loss of organic substrate oxidized by oxygen instead of nitrate, which would change the MR. Thus, an apparent minimum COD/N ratio (MR_A), taking into account the recycled oxygen effect, could be calculated when recycling rate is high.

If 1 g O_2 is assumed to allow the removal of about 2 g COD ($Y_{COD}/O_2 = 2$) [44–46], an additional organic matter supply is then required and the MRA is given by:

$$MR_A = MR_{exo}\left[\frac{R}{R+1} - NUR_{endo}\frac{aHRT}{S_{NH_{4,i}}}\right] + Y_{COD/O_2}\frac{R\ DO}{S_{NH_{4,i}}} \tag{10}$$

where DO is the concentration of dissolved oxygen in the aerobic tank and $S_{NH4,i}$ is the ammonia concentration in the feed.

Thus, experiments were conducted with COD/N ratios of 5 and 3.5, whereas the minimum required ratio, calculated using Eq. (10), is 4.09 and 4.06 at SRT of 40 and 60 d, respectively.

3.3. Reducing MR strategies

For the purpose of improving nitrate removal, two solutions can be put forward. First, the recirculation of nitrates from the aerobic tank to the anoxic one could be increased. But in this case the MR_A must be adjusted according to Eq. (10), as denitrification is limited by the amount of influent COD.

Then, in order to minimize the COD loss by oxygen brought from the aerobic compartment, the sludge return within the anoxic tank could be separated from the influent entrance, as shown in Fig. 5. Oxygen introduced in the newly defined compartment, having a volume V_1, would be consumed by endogenous respiration of active biomass. The volume, V_1, should be optimized in order to obtain best denitrification performances.

The second strategy is to boost endogenous denitrification, on one hand in the anoxic tank by increasing the anoxic hydraulic retention time, and on the other hand in the aerobic tank by setting a DO concentration level close to the oxygen half-saturation coefficient, K_{O_2}, in order to trigger the Simultaneous Nitrification and Denitrification (SND) process controlled by tuning the I_{e-} function [47,48].

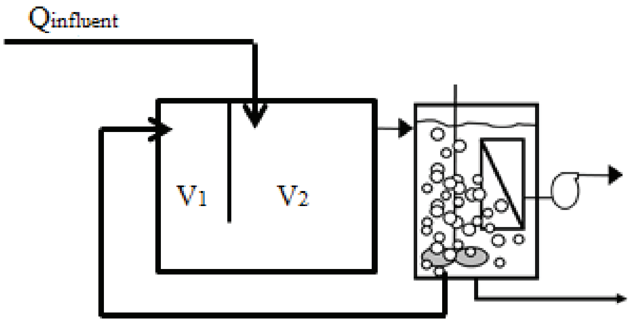

Fig. 5. Separation of the sludge return point from the influent in the anoxic tank.

4. Conclusion

The aim of this work was to assess the Minimum COD/N Ratio (MR) allowing complete denitrification in wastewater treatment. For this purpose, a modeling approach, using ASM3, was used. An apparent MR was defined considering all processes influencing nitrate removal including exogenous and endogenous denitrification along dissolved oxygen recirculation between aerobic and anoxic reactors. Simulations have shown that endogenous denitrification cannot be neglected when estimating the MR. It was demonstrated that the MR strongly depends on the following key operating parameters: solid retention time, anoxic hydraulic retention time, recirculation rate and dissolved oxygen concentration in the aerobic tank. Assessed MR values allowed predicting the nitrogen removal performances that were coherent with those obtained in a set of experimental campaigns conducted at two COD/N ratios.

Symbols

a	—	Anoxic volume fraction
ASM	—	Activated Sludge Model
ASM3	—	Activated Sludge Model No. 3
ASP	—	Advanced separation process
ATU	—	Allylthiourea
CAS	—	Conventional activated sludge process
COD	—	Chemical oxygen demand
DO	—	Dissolved oxygen
HRT	—	Hydraulic retention time
J_p	—	Permeate flow rate
MBR	—	Membrane biological reactor
MLSS	—	Mixed liquor suspended solids
MLVSS	—	Mixed liquor volatile suspended solids
MR	—	Minimum COD/N ratio
$\mathrm{MR_A}$	—	Apparent minimum COD/N ratio
$\mathrm{MR_{exo}}$	—	Minimum exogenous COD/N ratio
NLR	—	Nitrogen loading rate
$\mathrm{N{-}NH_4^+}$	—	Ammonia nitrogen
$\mathrm{N{-}NO_2^-}$	—	Nitrite nitrogen
$\mathrm{N{-}NO_3^-}$	—	Nitrate nitrogen
$\mathrm{N{-}NO_x}$	—	Nitrite and nitrate nitrogen
$\mathrm{NUR_{endo}}$	—	Endogenous uptake rate
OLR	—	Organic loading rate
ORP	—	Oxydation reduction potential
OUR	—	Oxygen uptake rate
$\mathrm{OUR_{endo',\ A}}$	—	Endogenous oxygen uptake rate of autotrophic biomass
$\mathrm{OUR_{endo',\ H}}$	—	Endogenous oxygen uptake rate of heterotrophic biomass
R	—	Recirculation rate
SD	—	Standard deviation
SND	—	Simultaneous nitrification and denitrification process
$S_{\mathrm{NH4,i}}$	—	Ammonia concentration in the influent
$S_{\mathrm{NOx,e}}$	—	Nitrate concentration in the effluent
*S*RT	—	Solid Retention Time
V_1	—	Anoxic volume where the sludge return occurs
V_2	—	Anoxic volume where the feed point is set
$\mathrm{V_{anoxic\ volume}}$	—	Anoxic compartment Volume
$\mathrm{V_{total\ volume}}$	—	Total reaction Volume (aerobic and anoxic volume)
WWTP	—	WasteWater treatment plant

ASM3 notation

$\mathrm{b_{A,NOx}}$	—	Endogenous respiration rate of autotrophic biomass in anoxic conditions ($\mathrm{d^{-1}}$)
$\mathrm{b_{A,O2}}$	—	Endogenous respiration rate of autotrophic biomass in aerobic conditions ($\mathrm{d^{-1}}$)
$\mathrm{b_{H,NOx}}$	—	Endogenous respiration rate of heterotrophic biomass in anoxic conditions ($\mathrm{d^{-1}}$)
$\mathrm{b_{H,O_2}}$	—	Endogenous respiration rate of heterotrophic biomass in aerobic conditions ($\mathrm{d^{-1}}$)
$\mathrm{b_{STO,NOx}}$	—	Endogenous respiration rate of storage compounds in anoxic conditions ($\mathrm{d^{-1}}$)
$\mathrm{b_{STO,O_2}}$	—	Endogenous respiration rate of storage compounds in aerobic conditions ($\mathrm{d^{-1}}$)
f_{XI}	—	Fraction of inert organics generated in biomass decay (–)
I_{e-}	—	On/Off switching function shifting from aerobic conditions to anoxic conditions (–)
$K_{\mathrm{O_2}}$	—	Oxygen half-saturation coefficient (mg $\mathrm{O_2}$/L)
K_{S}	—	Soluble substrate half-saturation coefficient (mg COD/L)
k_{STO}	—	Rate constant for organic compound storage ($\mathrm{d^{-1}}$)
S_{S}	—	Soluble biodegradable organics (mg COD/L)
S_{NOx}	—	Nitrate and nitrite (considered to be $\mathrm{NO_3^-}$ only for stoichiometry) (mg N/L)
X_{A}	—	Autotrophic nitrifying biomass (mg COD/L)
X_{H}	—	Ordinary heterotrophic biomass (mg COD/L)
X_{I}	—	Particulate inert organics (mg COD/L)
X_{STO}	—	Storage products (mg COD/L)
$Y_{\mathrm{COD/O_2}}$	—	Ratio of soluble substrate oxidized by dissolved oxygen (g $\mathrm{O_2}$/g COD)
Y_{H}	—	Yield of heterotrophic growth on storage products (g X_{H}/g X_{STO})
$Y_{\mathrm{H,NOx}}$	—	Anoxic yield of heterotrophic growth on storage products (g X_{H}/g X_{STO})
Y_{STO}	—	Yield coefficient for storage (g X_{STO}/g S_{S})
$\mathrm{Y_{STO,NOx}}$	—	Anoxic yield coefficient for storage (g X_{STO}/g S_{S})
μH	—	Heterotrophic maximum growth rate ($\mathrm{d^{-1}}$)

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