

Validating the Colloid model to optimise the design and operation of both moving-bed biofilm reactor and integrated fixed-film activated sludge systems

J. Albizuri, P. Grau, M. Christensson and L. Larrea

ABSTRACT

The paper presents a systematic study of simulations, using a previously calibrated Colloid model, from which it was found that: (i) for pure moving-bed biofilm reactor (MBBR) processes with tertiary nitrification conditions (no influent chemical oxygen demand (COD)), dissolved oxygen = 5 mg/L and residual $\text{NH}_4\text{-N} > 4$ mgN/L, a nitrification rate of 1.2 gN/(m² d) was obtained at 10 °C. This rate decreases sharply when residual $\text{NH}_4\text{-N}$ is lower than 2 mgN/L, (ii) for MBBR systems with predenitrification–nitrification zones and COD in the influent (soluble and particulate), the nitrification rate (0.6 gN/(m² d)) is half of that in tertiary nitrification due to the effect of influent colloidal X_S (particulate slowly biodegradable COD) and (iii) for integrated fixed-film activated sludge (IFAS) processes the nitrification rate in the biofilm (0.72 gN/(m² d)) is 20% higher than for the pure MBBR due to the lower effect of influent X_S since it is adsorbed onto flocs. However, it is still 40% lower than the tertiary nitrification rate. In the IFAS, the fraction of the nitrification rate in suspension ranges from 10 to 70% when the aerobic solids retention time varies from 1.4 to 6 days.

Key words | Colloid model, IFAS, MBBR, nutrient removal

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INTRODUCTION

Moving-bed biofilm reactor (MBBR) and integrated fixed-film activated sludge (IFAS) processes have been increasingly applied for nitrogen removal from municipal wastewater both in the case of new plants and in the upgrading of existing plants. To optimise their design and operation through simulations, different models have been proposed in the literature in recent years.

With regard to the pure MBBR processes for nitrogen removal, including predenitrification and nitrification zones, Maurer *et al.* (1999) and Larrea *et al.* (2007) employed the mixed-culture biofilm (MCB) model (Wanner & Reichert 1996), considering attachment and diffusion phenomena for particulate components in order to take into account the effect of influent X_S (particulate slowly biodegradable chemical oxygen demand (COD)) on nitrification and denitrification rates in the biofilm. The existence of such an effect has been experimentally observed by many authors (Abad 2004; Boltz & La Motta 2007).

Regarding the modelling of the IFAS processes, most authors (Boltz *et al.* 2009; Boltz *et al.* 2011) assume that influent X_S is entirely adsorbed onto flocs in suspension, and, in

addition, they do not consider attachment of the flocs towards the biofilm, which means that the nitrification rate in the biofilm is not dependent on the applied X_S load in the influent wastewater. However, Suzuki *et al.* (1999) found that the nitrification rates in the biofilm were in the simulations higher than in the experimental tests. They attributed this to the fact that interaction of influent X_S with the biofilm was not considered in simulations and took place in reality.

Albizuri *et al.* (2009) found that the description of the nitrate production and oxygen uptake rates in batch tests of an IFAS Johannesburg process was not correct when using the original MCB model and taking into account the attachment and diffusion phenomena. For this reason, they proposed the Colloid model, where the colloids present in the influent wastewater interact both with the biofilm and the flocs through attachment and detachment phenomena (Figure 1). Thus, in this model, different particulate components (X_i) have three possible states: colloids ($X_{i,C}$), flocs ($X_{i,F}$) and biofilm ($X_{i,B}$). The hypothesis was to consider as colloids those suspended solids which remain in the supernatant of a settling test after 30 min. The test indicated

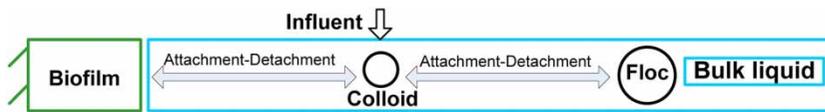


Figure 1 | Diagram of different interactions between the colloids, the flocs and the biofilm in the Colloid model.

that around 50% of the influent particulate components were of colloidal nature.

This model described satisfactorily the experimental results obtained in the IFAS Johannesburg pilot plant. A slight parameter adjustment (Albizuri 2012) allowed also the correct description of other experimental results with IFAS Bardenpho (Albizuri *et al.* 2010) and pure MBBR pre-denitrification–nitrification (Larrea *et al.* 2007) pilot plants.

In the current paper, this Colloid model, including the last set of parameter values, has been used in order to accomplish the following objectives. The first objective is to analyse via simulations the effect of dissolved oxygen (DO), residual ammonium ($\text{NH}_4\text{-N}$) and readily biodegradable COD (S_S) concentrations on the nitrification rate in the biofilm.

The second objective is to analyse the effect of particulate slowly biodegradable COD (X_S) on the nitrification and denitrification rates both in pure MBBR and IFAS processes.

And the third objective is to analyse the effect of the aerobic solids retention time (SRT) on the nitrification rates in the mixed liquor suspended solids (MLSS) and on the biofilm in IFAS processes. This has given rise to determination of the optimum criteria to optimise the design and operation of IFAS processes.

The results obtained from these simulations quantitatively agree with other experimental results in the literature, thus confirming the high validation degree of the model.

MATERIALS AND METHODS

As mentioned above, for all the simulations in the present paper, the Colloid model (Albizuri *et al.* 2009) with the last set of parameter values (Albizuri 2012) and implemented in the WEST (World Wide Engine for Simulation, Training and Automation) simulation platform was used.

Firstly, simulations with one aerobic pure MBBR reactor were carried out. The reactor was fed with synthetic wastewater (no influent particulate COD) and operated with a carrier specific volumetric surface area of $250 \text{ m}^2/\text{m}^3$, a hydraulic retention time (HRT) of 2 hours and a temperature of 10°C . In particular, in these simulations the uncoupled quantitative effects on the biofilm nitrification

rates of the residual $\text{NH}_4\text{-N}$, DO and applied soluble readily biodegradable COD (S_S) concentrations were tested.

Subsequently, the quantitative effect of X_S on the nitrification rate in the biofilm, both in pure MBBR and IFAS processes, configured as pre-denitrification – two-stage nitrification (D-N-N), was studied. For this purpose, real wastewater from Bilbao's WWTP was considered. This required the conversion of measured wastewater characteristics into Activated Sludge Model No. 2d (ASM2d) model parameters. The water was characterized by a high concentration of total suspended solids (TSS) (around 170 mg/L), from which 50% was assumed to be of colloidal nature, according to the settling test above-mentioned, and to interact with the biofilm through attachment and diffusion phenomena (Albizuri *et al.* 2009). The aerobic fraction in both cases was 50% and the total HRT was 4 hours. The only difference between the MBBR and the IFAS was that in the IFAS process, unlike in the pure MBBR, an external sludge recirculation was implemented reaching a MLSS concentration of 3.5 g/L. This gives rise to a total SRT of 3.4 days.

In addition, with the IFAS process, the effect of the aerobic SRT (from 1.4 to 6 days) on the nitrification rate in suspension (MLSS) and in the biofilm was studied. The HRT in this study was fixed at 8 hours and the SRT was changed by means of varying the MLSS concentration in suspension from 1.5 to 5.5 g/L.

RESULTS AND DISCUSSION

Effect of DO, effluent residual $\text{NH}_4\text{-N}$ and influent soluble readily biodegradable COD on the nitrification rate in the biofilm

To study the effect of the residual $\text{NH}_4\text{-N}$ on the nitrification rate in the biofilm, influent $\text{NH}_4\text{-N}$ concentrations in different simulations were varied between 10 and 50 mg/L. Figure 2(a) shows that for the nitrification rate (calculated by the simulation tool via nitrification kinetics based on ASM2d model) there are two clearly differentiated zones depending on the residual ammonium concentration in the bulk liquid. When $\text{NH}_4\text{-N}$ concentration is higher than 4 mgN/L, nitrification rate reaches a maximum value, due

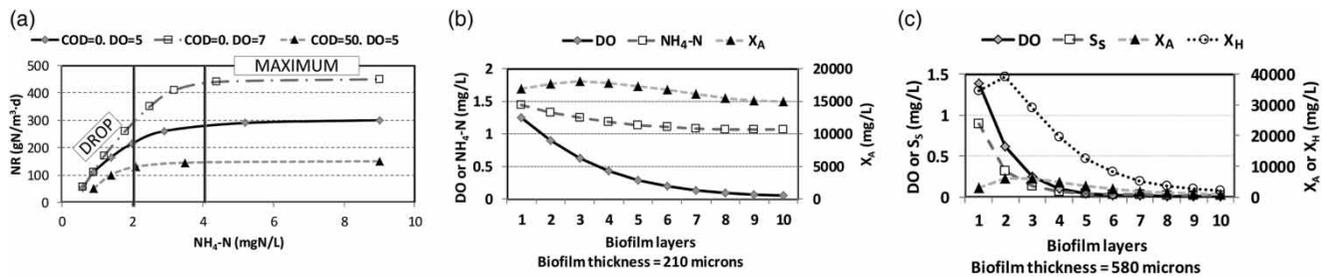


Figure 2 | (a) Nitrification rate (NR) vs residual NH₄-N at different DO and COD concentrations, (b) component profiles in the biofilm for DO = 5 mg/L and influent COD = 0 mg/L and (c) component profiles in the biofilm for DO = 5 mg/L and influent COD = 50 mg/L. Note (b) and (c) biofilm profiles: biofilm divided into 10 layers; layer 1: biofilm surface layer and layer 10: biofilm bottom layer.

to DO limitation at the bottom of the biofilm (Figure 2(b)). This means that an increase in the influent NH₄-N load does not give rise to a proportional increase in the nitrification rate in the biofilm, as would occur in the suspended solids operating with enough SRT to nitrify. This is due to the oxygen transfer limitation in the inner layers of the biofilms even with DO concentrations in the bulk liquid above 5 mg/L, whereas in the suspended solids, given the smaller size of the flocs, a DO concentration around 2 mg/L would be enough to have a non-limited nitrification rate. In the case of tertiary nitrification (COD = 0), the maximum rate with a DO concentration of 5 mg/L is 300 gN/(m³ d) (Figure 2(a), 1.2 gN/(m² d)), and an increase of the DO concentration from 5 to 7 mg/L results in an increase of 50% in the nitrification rate (450 gN/(m³ d)/1.8 gN/(m² d)) due to the lower limitation of the DO inside the biofilm. This indicates an increased ratio of the nitrification rate per unit of increased concentration of DO of 75 gN/(m³ d)/1 gO₂/m³, which agrees with the experimental results obtained by Hem et al. (1994) (60 gN/(m³ d)/1 gO₂/m³) in a MBBR run at similar conditions.

With a DO concentration of 5 mg/L, when influent S_s is increased from 0 to 50 mg/L (secondary nitrification), the nitrification rate on the biofilm is practically reduced to half (Figure 2(a), 150 gN/(m³ d)/0.6 gN/(m² d)). This occurs due to the higher availability of S_s inside the biofilm (Figure 2(c)), giving rise to a significant growth of heterotrophic bacteria (X_H) at the surface of the biofilm, which compete against nitrifiers (X_A) for DO. This indicates that the decrease ratio on the nitrification rate per unit of increased COD load to the reactor is 0.25 gN/(m³ d)/gCOD/(m³ d), which agrees with the ratio resulting from the experimental studies by Hem et al. (1994) (0.2 gN/(m³ d)/gCOD/(m³ d)).

For all the cases above-mentioned, with ammonium concentrations below 2 mgN/L, a decrease in the ammonium concentration gives rise to a sharp drop of the nitrification rate (Figure 2(a)). The decrease ratio per unit

of decreased ammonia concentration is 150 gN/(m³ d)/gN/m³, which agrees with the results presented by Hem et al. (1994) (140 gN/(m³ d)/gN/m³). Therefore, in order to maintain high nitrification rates in the biofilm it is recommended to operate with residual NH₄-N concentration in the range of 2–3 mgN/L.

Predenitrification–nitrification in the biofilm of the pure MBBR

Regarding the MBBR D-N-N process fed by real wastewater, TSS concentration in the bulk liquid (220 mg/L) was slightly higher than the concentration in the influent (170 mg/L), due to the contribution of the solids detached from the biofilm. From this total TSS concentration, the colloidal X_S (X_{Sc}) fraction was around 25% and it is this fraction which interacts with the biofilm in different reactors.

With regard to the anoxic reactor (Ax), Figure 3(a) shows that soluble COD is mostly removed in the anoxic reactor while the X_{Sc} is only partially removed. The corresponding kinetic equations indicate that 50% of the heterotrophic bacteria grow on soluble COD and the remaining 50% on colloidal X_S, giving rise to X_H concentration in the biofilm of this reactor (5,500 mg/L) and a denitrification rate around 200 gN/(m³ d).

Focusing on the aerobic reactors, the colloidal X_S from the anoxic reactor is partially removed in both aerobic reactors (Figure 3(a), Ae1 and Ae2), giving rise to a significant concentration of X_H in the biofilms (1,500–2,500 mg/L). Consequently, in this specific case with high TSS and X_{Sc} concentrations in the influent, the nitrification rate in the biofilm of the first aerobic reactor, with no limitation of NH₄-N, is around 0.6 gN/(m² d) (Figure 3(c)), which is basically half the rate obtained in the tertiary nitrification case (Figure 3(c), 1.2 gN/(m² d)). Taking into account that soluble COD has been already mostly consumed in the anoxic reactor for denitrification (Figure 3(a)), this confirms

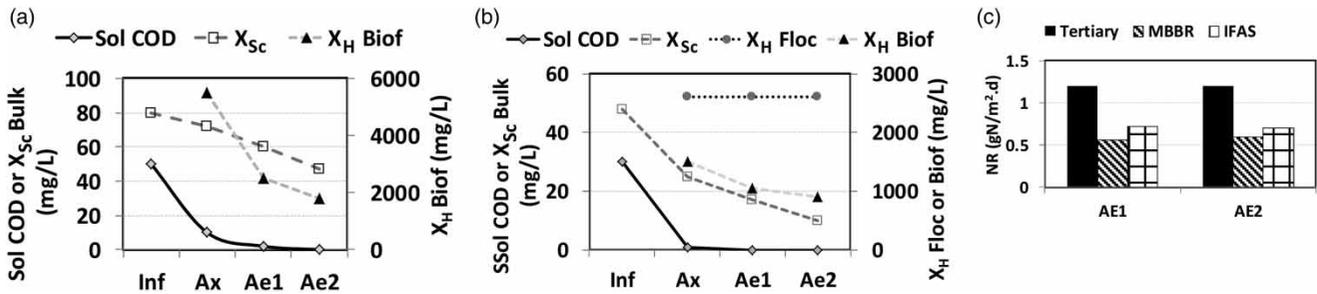


Figure 3 | Different component concentrations along different reactors in (a) pure MBBR and (b) IFAS, and (c) nitrification rates in the biofilm in tertiary nitrification, MBBR and IFAS cases.

that, in this specific case of high colloidal X_S concentration in the influent, the interaction of the colloidal X_S with the biofilm has a relatively high effect on the nitrification rate in the biofilm.

In the second aerobic reactor, although X_H concentration is lower (Figure 3(a)), the nitrification rate achieved is not higher (Figure 3(c), $0.62 \text{ gN}/(\text{m}^2 \text{ d})$) due to a slightly higher limitation of $\text{NH}_4\text{-N}$. The value of the nitrification rate of around $0.6 \text{ gN}/(\text{m}^2 \text{ d})$ agrees with the rate obtained by Rusten *et al.* (2000) ($0.55 \text{ gN}/(\text{m}^2 \text{ d})$) for a predenitrification–nitrification configuration with primary treated influent wastewater and similar operational conditions.

Predenitrification–nitrification in the IFAS

In the IFAS process, with the same operational conditions as in the MBBR except for the higher MLSS concentration (3.5 g/L), colloidal X_S concentration in all the reactors (Figure 3(b), $10\text{--}25 \text{ mg/L}$) is much lower than in the pure MBBR (Figure 3(a), $45\text{--}70 \text{ mg/L}$) due to the higher adsorption of the X_S onto flocs ($\text{MLSS} = 3.5 \text{ g/L}$). Consequently, the interaction between colloidal X_S and the biofilm is lower in the IFAS process than in the pure MBBR. This gives rise to a concentration of heterotrophic bacteria in the biofilm of the three reactors of IFAS (Figure 3(b), $900\text{--}1,500 \text{ mg/L}$) between two and three times lower than in the pure MBBR (Figure 3(a), $1,500\text{--}5,500 \text{ mg/L}$), and accordingly to lower biofilm thicknesses ($300\text{--}400$ microns in IFAS vs. $500\text{--}1,000$ microns in MBBR). Thus, in the IFAS process X_H activity was mainly located in the solids in suspension (Figure 3(b), $2,600 \text{ mg/L}$) while in the pure MBBR they were mainly directed to the biofilm.

With regard to the anoxic reactor, this gives rise to the fact that in the IFAS only around 20% of the total denitrification rate ($300 \text{ gN}/(\text{m}^3 \text{ d})$) occurs in the biofilm. Therefore, in an IFAS process, it is considered that the addition of the carriers in the anoxic zone is not feasible economically.

Focusing on the aerobic reactors, the lower heterotrophic activity in the biofilm gives rise to a nitrification rate in the biofilm of the first reactor (with no $\text{NH}_4\text{-N}$ limitation) (Figure 3(c), $180 \text{ gN}/(\text{m}^3 \text{ d})/0.72 \text{ gN}/(\text{m}^2 \text{ d})$) around 20% higher than in the MBBR (Figure 3(c), $150 \text{ gN}/(\text{m}^3 \text{ d})/0.6 \text{ gN}/(\text{m}^2 \text{ d})$). However, in this specific case of high colloidal X_S concentration in the influent, the rate is still 40% lower than in tertiary nitrification (Figure 3(c), $300 \text{ gN}/(\text{m}^3 \text{ d})/1.2 \text{ gN}/(\text{m}^2 \text{ d})$). It is highlighted that in simulations, using the hypothesis of the influent X_S being entirely adsorbed onto the flocs in suspension, and in addition not considering any attachment of the flocs towards the biofilm (Boltz *et al.* 2009), the same nitrification rate as in the tertiary nitrification case was achieved. The nitrification rate in the second biofilm (Figure 3(c), $0.7 \text{ gN}/(\text{m}^2 \text{ d})$) is again (like in the MBBR) similar to the rate in the first biofilm, because of the offset of lower X_H concentration (Figure 3(b)) and lower residual $\text{NH}_4\text{-N}$.

Therefore, it can be concluded that although the effect of the colloidal X_S on the nitrification rate in the biofilm of the IFAS is lower than on the MBBR, it is not negligible. This agrees with the consideration of Suzuki *et al.* (1999), who hypothesized that nitrification rates in the biofilm of IFAS processes were affected by the influent particulate components.

Regarding the nitrification rate in suspension, in the pure MBBR process there is no nitrification occurring in the solids in suspension due to the low SRT, equal to the HRT (4 hours). In the IFAS process, this rate depends on the SRT and MLSS, as explained in the next chapter.

Effect of the aerobic SRT on the nitrification rate in suspension and on the biofilm in the IFAS

With regard to the biofilm of the first reactor (Biof_AE1), Figure 4(a) shows that the nitrification rate ($200 \text{ gN}/(\text{m}^3 \text{ d})/0.8 \text{ gN}/(\text{m}^2 \text{ d})$) is almost independent of the aerobic SRT since the biofilm of this reactor is operating at $\text{NH}_4\text{-N}$ concentrations above 4 mgN/L even at the aerobic SRT of

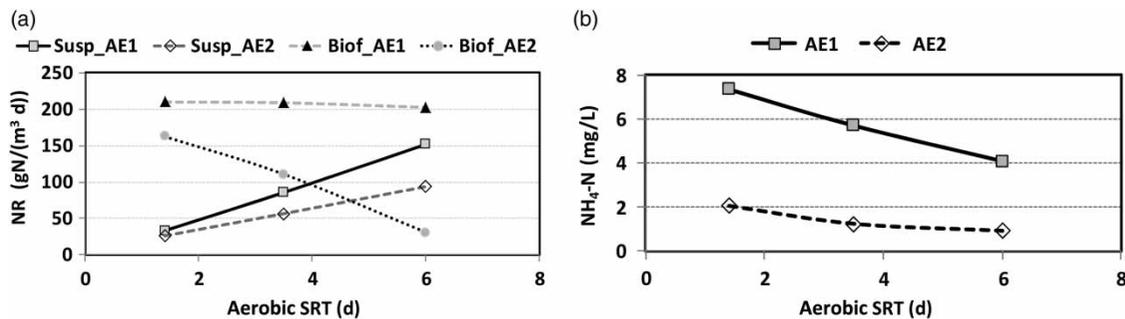


Figure 4 | (a) Nitrification rates (NR) in suspension and biofilm and (b) residual $\text{NH}_4\text{-N}$ concentration in the bulk liquid of both aerobic reactors vs aerobic SRT.

6 days (Figure 4(b)), which means that there is no limitation for the nitrifiers in this biofilm. The nitrification rate in this case (HRT = 8 hours, $0.8 \text{ gN}/(\text{m}^2 \text{ d})$) is slightly higher than the above-mentioned rate at the HRT of 4 hours (Figure 3(c), $0.72 \text{ gN}/(\text{m}^2 \text{ d})$) due to the lower COD load applied at the higher HRT.

Figure 4(a) also shows that the nitrification rate in suspension (Susp_AE1/AE2) is highly dependent on the aerobic SRT. For an aerobic SRT of 1.4 days, lower than the critical SRT to nitrify, defined as $1/(\mu_A - b_A) = 3.4$ days at 10°C (μ_A = maximum growth rate of nitrifying bacteria, b_A = decay rate of nitrifying bacteria), the nitrification rate in suspension in both reactors is around $40 \text{ gN}/(\text{m}^3 \text{ d})$ while in a conventional activated sludge process at this aerobic SRT there would not be any nitrification at all. This is due to the nitrifier bacteria detachment from the biofilm to suspension and their accumulation with the sludge recirculation in the IFAS process.

The increase of the aerobic SRT to 3.5 and 6 days causes a linear rise in the nitrification rates in suspension in both reactors (Figure 4(a)) due to the fact that in these cases the aerobic SRT is, respectively, similar and higher than the critical SRT to nitrify (3.4 days at 10°C). This promotes the growth of nitrifiers in suspension, as would occur in a conventional activated sludge process. Consequently, the ammonium concentration in the bulk liquid of the second reactor decreases from 2 to $0.8 \text{ mgN}/\text{L}$ (Figure 4(b)), which gives rise to a sharp reduction of the nitrification rate in the biofilm of the second reactor (Figure 4(a), Biof_AE2). This lower ammonium concentration in the second reactor at higher SRT values also makes the linear increase of the nitrification rate in suspension in the second reactor be lower than that in the first reactor (Figure 4(a), Susp_AE1/AE2).

For the specific case of the aerobic SRT of 6 days, the nitrification rate in the biofilm of the second reactor is as low as $30 \text{ gN}/(\text{m}^3 \text{ d})$ (Figure 4(a), $0.12 \text{ gN}/(\text{m}^2 \text{ d})$). Thus, the process does not take advantage of the high potential of the

carriers to nitrify, and its behaviour is closer to a conventional activated sludge reactor. Therefore, as mentioned above for the pure MBBR, it is recommended to operate the IFAS reactors at $\text{NH}_4\text{-N}$ concentrations between 2 and $3 \text{ mg}/\text{L}$. Figure 4(b) shows that for the aerobic SRT of 1.4 days and the nitrification rate in the biofilm of the second reactor is moderate (Figure 4(a), $160 \text{ gN}/(\text{m}^3 \text{ d})$ or $0.65 \text{ gN}/(\text{m}^2 \text{ d})$). Nevertheless, aerobic SRT values lower than the critical one (3.4 days) may give rise to bad sludge settling characteristics and bad performance of the secondary settler. For this reason, it is recommended to operate with an aerobic SRT close to the critical SRT (3.4 days), which agrees with the performance of several full-scale plants presented by Odegaard (2009). At this aerobic SRT of 3.4 days, the nitrification rate in MLSS ranges between 60 and $90 \text{ gN}/(\text{m}^3 \text{ d})$ (Figure 4(a), first and second reactors) and in the biofilm between 120 and $200 \text{ gN}/(\text{m}^3 \text{ d})$. These numbers agree with the design nitrification rates proposed by Odegaard (2009) for full-scale IFAS plants, $50\text{--}80 \text{ gN}/(\text{m}^3 \text{ d})$ for MLSS and $90\text{--}140 \text{ gN}/(\text{m}^3 \text{ d})$ for the biofilm.

In summary, to optimise the design and operation of IFAS processes via simulations, both criteria ($\text{NH}_4\text{-N} \approx 2\text{--}3 \text{ mg}/\text{L}$ and aerobic SRT \approx critical SRT) can be applied by means of the adjustment of the aerobic HRT, the carrier surface area, the DO concentration and the total SRT.

CONCLUSIONS

The Colloid model describes satisfactorily not only a wide range of experimental results obtained in MBBR and IFAS pilot studies carried out at CEIT (Centro de Estudios e Investigaciones Técnicas de Gipuzkoa) but also the results obtained by other authors. This shows that the validation degree of this model is relatively high. A systematic simulation study, carried out with this model, showed that

the nitrification rate at 10 °C in the pure MBBR process with predenitrification–nitrification zones (0.6 gN/(m² d)) is half of that obtained in tertiary nitrification, due to the effect of influent colloidal X_S.

In IFAS processes, a lower effect of X_S takes place because of its adsorption onto the flocs. Consequently, the nitrification rate in the biofilm (0.72 gN/(m² d)) increases 20% with respect to that in the MBBR, but it is still 40% lower than that obtained when the hypothesis of total adsorption of influent X_S onto flocs and no attachment of flocs to the biofilm is applied (1.2 gN/(m² d)).

The nitrification rate in the biofilm is highly affected by the DO and residual NH₄-N concentration in the reactor, so that residual NH₄-N concentration of 2–3 mgN/L is recommended. Nitrification rate in suspension depends on the aerobic SRT for which a value near the critical SRT to nitrify, $1/(\mu_A - b_A)$, is recommended. In this case, the nitrification rate in suspension amounts to about 40% of that in the biofilm. These criteria allow the optimisation of the design and operation of MBBR and IFAS processes for nutrient removal.

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