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Effect of effluent and sludge recirculation ratios on integrated fixed films A2O system nutrients removal efficiency treating sewage

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ABSTRACT

Anaerobic-anoxic-oxic (A2O) reactors are commonly used to remove nutrients from wastewater due to their high biological nutrient removal (BNR) potential as compared with conventional activated sludge. A2O often allows sludge and treated effluent recirculation to enhance biological total nitrogen (TN) and total phosphorous (TP) removal. Addition of fixed film in A2O reactors promotes attached biomass growth and accelerates BNR process. A bench scaled A2O reactor with integrated fixed film in all three zones was set to evaluate the effect of the effluent and secondary sludge recirculation rate to the chemical oxygen demand (COD), TN, TP removal efficiency. Five different recirculation scenarios were tested, sludge-effluent:influent of 0%, 10%, 20%, 30%, and 40%. The results showed that COD, TN, and TP can be in principle reduced without recirculation; however, the effluent is significantly polished when a recirculation stream is added at an optimum of 30%, achieving a maximum of 92.0%, 97.7%, and 74.6% removal for COD, total Kjeldahl nitrogen, and TP, respectively. Further increase of the recirculation ratio does not significantly improve the treatment process.

Keywords: Integrated fixed film A2O; Recirculation ration; Nutrients removal; Sewage

1. Introduction

Water quality tends to become a major global environmental concern [1–3]. For the last two decades biodegradation of pollutants is an important, economical, and efficient way to tackle pollution [4,5]. Discharge of untreated municipal wastewater results in eutrophication due to uncontrolled bloom of algae and other phototrophic organisms growth [6,7]. The main constituents of eutrophication are nitrogen (N) and phosphorus (P) [8–14]. Removal of nitrogen and phosphorus from wastewater through microorganisms/bacteria is known as biological nutrient removal (BNR) process [7]. Nitrification and denitrification are the key processes to remove nitrogen. Nitrification is the oxidation of ammonia into nitrite, and nitrate which is conducted by two types of aerobic bacteria (chemo-litho-autotrophic). The first group converts ammonia to nitrite (ammonia oxidizing bacteria (AOB)), further oxidation of nitrite to nitrate is carried out by another bacterial group (nitrite oxidizing bacteria (NOB)). Denitrification is series of reduction processes, in which nitrite and nitrate are reduced to inert nitrogen (N_2) gas [15].

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Nitrification is considered rate limiting in BNR compared with denitrification. The first is dictated by the AOB, highly affected by both environmental and operational factors organisms [7]. AOBs lack of functional diversity and have stringent growth requirements [16]; hence, adaptation to random environmental parameters is challenging.

BNR processes are generally divided into two categories, (1) the suspended (in suspension), and the (2) attached growth (biofilm) [17,18]. Based on these two, numerous biological treatment technologies have been developed to realize nutrients removal from wastewater [19]. Up to date, nitrification–denitrification is realized through nitrite accumulation from multiphase processes, that is, anaerobic-anoxic-oxic (A2O) [19]. A2O is characterized as efficient and reliable for BNR as it recycles electron acceptors (oxygen and nitrite/nitrates) within distinct reactor chambers [20]. This result in lower operational costs as compared with conventional aerobic treatment processes due to the uptake of carbon at all phases (anaerobic, anoxic, and oxic). Such reactor schemes provide with consistent nitrogen and phosphorus removal, produce less sludge, and require shorter retention time [21,22].

Each process zone (chambers) of the A2O can be further divided to subsections based on application. The anaerobic zone is often the first tank, situated before the anoxic zone, assisting to the release of phosphorus from polyphosphates. In the same zone, the phosphate accumulating organisms (PAOs) convert organic matter, that is, volatile fatty acids (VFAs) to polyhydroxylalkanoate (PHAs). PAOs utilize energy produced from the polyphosphate breakdown to convert organic matter to PHAs [23]. In the anoxic zone, often situated after the anaerobic zone, denitrifying polyphosphate accumulating organisms use nitrates and nitrites as electron acceptors instead of dissolved oxygen to accumulate phosphorus [24–26]. Finally at the aerobic zone (usually in the end of the stream), PAOs utilize the stored PHAs as energy to uptake the phosphorus which was released in the anaerobic zone as well as any other phosphorus present in the aerobic zone [27]. Returning sludge in the anaerobic zones replenishes the polyphosphate pool and the process is repeated. As previously stated, the process employs nitrate/nitrite to oxidize stored PHAs, thereby denitrification and phosphorus removal occur concurrently [28,29]. The reaction takes place in the anoxic zone instead of the aerobic [16,30].

A recent optimization is the integration of fixed film in the A2O systems [31]. This resulted to numerous advantages as compared with suspended growth, that is, lower energy requirement, limited sludge production, smaller surface footprint, ease in handling inconsistent influent (hydraulically or loading), longer biomass retention, operation stability, robustness against toxic substances, as well as higher removal efficiencies [32]. Media with high surface:volume ratios do increase the concentration of microorganism (mixed liquor volatile suspended solids) , leading to adequate BNR at reduced reactor volumes. Fixed film reactors are often employed as secondary and/or tertiary treatment for organic and nutrients removal applications [33–37].

Due to the cost effectiveness of the method much attention has been given for process optimization [38,39]. Special attention has been given to the effect of different organic loadings and retention time on the treatment of cooking wastewater [31], as well as to the effect of hydraulic retention time (HRT) on nutrients and carbon removal from domestic wastewater [40].

Not considerable work has been carried out in the field of recirculation streams recirculation, only recently setup [41]. Generally, recirculation of the effluent from the aerobic chamber (internal recycle) drives the produced NO_2, NO_3 to the anoxic chamber for denitrification; the recirculation of the sludge from secondary clarifier to the anaerobic chamber (external recycle) returns the viable microbes to the anaerobic chamber for P-uptake [42]. To the best of our knowledge, no study has evaluated the effect of varying recirculation ratios of internal and external recycle in integrated fixed film A2O.

The current study focuses in the investigation of the nutrient removal efficiency (carbon, total phosphorous (TP), total nitrogen (TN) from wastewater) of an integrated fixed film A2O system at different sludge (external recycle) and effluent (internal recycle) recirculation regimes. Polyethylene sheets were used as fixed film in all zones of A2O process.

Optimizing recirculation would assist in the realization of further polished wastewater effluents at reduced recirculation costs. Minimizing the cost of A2O would increase the sustainable character of the process, making it more favorable among other conventional wastewater treatment options.

2. Materials and methods

2.1. Experimental setup

A lab scale setup of A2O comprising of three individual bioreactors, an anaerobic, an anoxic, and an oxic (aerobic), was developed (Fig. 1) for A2O wastewater treatment application. The primary sedimentation tank was installed prior the anaerobic part, while the final clarifier was placed after the aerobic chamber of the system. The HRT of the anaerobic, anoxic, and oxic parts was 3, 3, and 6 h, respectively. The dimensions of the reactors were: anaerobic (0.15 m × 0.3 m × 0.53 m), anoxic (0.15 m × 0.3 m × 0.53 m), and aerobic (0.3 m × 0.3 m × 0.53 m). The retention time for the primary and secondary clarifier was selected as 3 h. Prior the process scheme a tank with a magnetic stirrer was set for actual raw sewage storage (details below). A peristaltic pump (BT100M, Boading CHuangrui precision pump Co., Ltd., China) was installed to drive the wastewater from the storage into the primary sedimentation tank; the overflow was by gravity guided to the bottom of the anaerobic tank. Similarly, water collected from the top of anaerobic tank was guided via piping to the bottom of the anoxic and finally to the aerobic tank.

The total volume of all the bioreactors was 80 L (excluding submerged filters volume). Two aerators/diffusers were fixed to introduce air at the bottom of the aerobic section to maintain the required DO in the range of 3–4 mg/L. As per the integrated fixed film, polyethylene sheets were fixed in a cast iron skeleton and submerged in all three bioreactor chambers. The thickness of the sheets was 1 mm and the distance between each plate was fixed at 5 mm. The dimensions of each sheet were 0.25 m × 0.3 m. The numbers of sheets

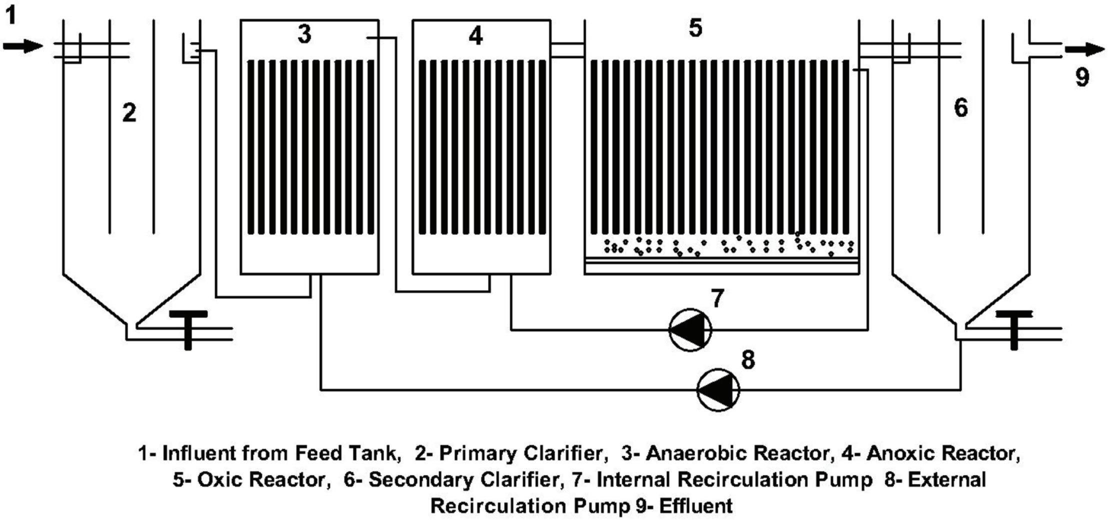

Fig. 1. Schematic diagram of A2O process experimental setup.

placed were: 12, 12, and 24 in the anaerobic, anoxic, and aerobic tanks, respectively.

2.2. Recirculation system

The flow was recycled through two different points as per recirculation origin; firstly, internal effluent recycling stream from the oxic reactor to the anoxic, secondly, the external secondary sludge recycling from the secondary sedimentation tank to anaerobic reactor. Internal and the external recycling ratios were kept equal at all trials; their absolute values were proportionally altered rendering them the key variables on this study.

2.3. Operational condition and plan

The volumetric organic load to the unified bioreactor (all chambers) was 0.65 kg COD (chemical oxygen demand)/m^3 d, while the attached media surface loading rate was 0.0165 kg COD/m^2 d. The hydraulic loading rate on the fixed film was 0.043 m^3/m^2 d. The effluent and sludge recirculation rate were the parameters of interest for the evaluation of their combined effect on COD and nutrients (total Kjeldahl nitrogen (TKN) and TP) removal. The different recirculation regime scenarios (for effluent and sludge) are given in Table 1.

2.4. Sampling

Samples for chemical analysis were collected from the inlet and the outlet of each chamber (anaerobic, anoxic, and oxic) thrice per day. After collection samples were mixed in equal proportion (10 mL each) to form a composite sample. Sample was then tested accordingly.

2.5. Analytical analysis of influent and effluent

Influent and effluent samples were analyzed using standard methods. Specifically, COD and phosphate were measured calorimetrically using spectrophotometer (DR 600, HACH, USA); TKN was analyzed using KjeltecTM 2100 (FOSS analytical AB, Sweden); and DO in the bioreactor was measured using a DO meter (Model 4320, Control company, USA).

Table 1
Description of the different recirculation scenarios investigated and the corresponding testing duration

S. No.	Description	Scenario	Run time (d)
1	Without recirculation	S0	80
2	10% effluent and sludge recirculation	S10	20
3	20% effluent and sludge recirculation	S20	20
4	30% effluent and sludge recirculation	S30	20
5	40% effluent and sludge recirculation	S40	20

2.6. Wastewater characteristics

Prior storage and feeding, the wastewater was screened by a mesh to separate all floating particles and grits that could promote inconsistency in composition as well as potential issues to the electromechanical equipment employed for the trial. The concentration of the key pollutants present in the sewage is given in Table 2.

2.7. Statistical analysis

For the statistical analysis of the observations and to support significance of the findings, a single factor analysis of variance (ANOVA) was applied. The ANOVA test was applied between all two contiguous scenarios (S0 and S10, S10 and S20, S20 and S30, and S30 and S40).

Table 2
Sewage characteristics

Parameters	Mean value[a]
COD (mg/L)	380 ± 45.5
TN (mg/L)	43.3 ± 6.45
TP (mg/L)	26 ± 6.7
pH	6.7–7.9

[a] *n* is number of sample that were 160; variance is expressed as standard variation.

3. Results

3.1. Scenario S0

COD and TP monitoring started after day 5, TKN monitoring started on day 18. The COD removal efficiency in each of the anaerobic, anoxic, and oxic zones during the early operational stage (5th–10th day) was estimated as 15.3% ± 1.2%, 21% ± 0.73%, 11.8% ± 2.25%, respectively. The overall efficiency from <20% increased to 48.2% ± 3.3% after day 10), while during the 70th to the 80th day of operation the overall removal reached its maximum of 63.2% ± 0.5%). At this last period, the removal efficiency from the individual chambers was 16.2% ± 2.4%, 19.4% ± 1.3%, and 28% ± 2.7% for the anaerobic, anoxic, and oxic phase, respectively (Fig. 2 S0(a)).

Similarly, the average TKN removal efficiencies reached the peak from the early experimental days (day 10) (5.0% ± 0.5%, 74.6% ± 0.6%, and 9.3% ± 1.1% for the anaerobic, anoxic, and oxic phase, respectively; overall of 88.9% ± 0.9% (Fig. 2 S0(b)). The performance was kept consistent until the finalization of this trial phase, the efficiency on days 18–28 for each phase did not significantly varied (5.6% (±1.0%), 72.1% (±1.0%), and 10.6% ± 1.4%, for anaerobic, anoxic, and oxic reactors, respectively, total removal efficiency of 88.3% ± 0.3%).

The average TP removal efficiencies for days 5–15 were: 12.6% ± 1.7%, 4.0% ± 2.1%, and 25.8% ± 4.5% for the anaerobic, anoxic, and oxic reactors, respectively, while the overall removal was 41.9% ± 4.2%. During the last 10 d of S0 scenario, the average TP removal increased reaching the 11.3% ± 2.0%, 7.6% ± 5.2%, and 40.5% ± 6.3% for the corresponding phases with the overall removal reaching the 59.3% ± 2.0% (Fig. 2 S0(c)).

3.2. Scenario S10

During the last 10 experimental days of this scenario the COD removal peaked with efficiencies at 21.9% ± 2.2%, 31.0% ± 1.7%, and 22.0% ± 1.6% for the anaerobic, anoxic, and oxic phase, respectively; the overall removal efficiency of 74.9% ± 0.6%. This was 12.0% more ($P < 0.05$; Table 3) as compared with the S0 (Fig. 2 S10(a)). TKN removal reached the 0.99% ± 0.5%, 84.4% ± 0.5%, and 9.4% ± 1.0% in the anaerobic, anoxic, and oxic reactor during last 10 d. The overall reactor removal increased up to 94.7% ± 0.7% in this scenario, 5.8% higher than what was observed at S0 ($P < 0.05$; Table 3). Similarly, in the case of TP removal the removal efficiency increased up to 68.8% ± 0.8%, this increment was significantly ($P < 0.05$; Table 3) higher than at S0 by 9.5%. Specifically, the observed TP removal efficiencies in the anaerobic, anoxic, and oxic reactors were: 15.8% (±1.6), 6.4% (±2.3), and 46.4% (±2.5), respectively (Fig. 2 S10(c)).

Table 3
ANOVA comparisons between removal efficiencies achieved at different recirculation regimes

Scenario	TP		TKN		COD	
	F_{crit}	p-Value	F_{crit}	p-Value	F_{crit}	p-Value
S0–S10	4.41	1.34E−10	4.41	1.82E−11	4.41	2.29E−20
S10–S20	4.41	0.008227	4.413	0.019332	4.41	2.96E−14
S20–S30	4.41	6.05E−14	4.41	0.000469	4.41	2.28E−08
S30–S40	1.5	0.225593	5.31	0.072341[a]	5.31	0.818544[a]

[a] The ANOVA was tested on last 5 d removal efficiencies.

3.3. Scenario S20

COD removal efficiency during the last 10 d of this scenario showed increased performance over S1 by 10% ($P < 0.05$; Table 3). The overall removal efficiency was 84.0% ± 1.1% and specifically 25.4% ± 3.0%, 26.3% ± 3.2%, and 32.4% ± 1.7% for the anaerobic, anoxic, and oxic reactors, respectively. Similarly, the TKN removal efficiencies were 4.0% ± 2.0%, 85.1% ± 1.6%, and 6.9% ± 2.8% in anaerobic, anoxic, and oxic reactors, respectively, accounting for an overall reduction of 95.9% ± 1.1%. This was significantly higher than what was observed for S0 ($P < 0.05$) and as compared with S10 ($P < 0.05$) but at a lower P-value (Table 3). The TP removal efficiency was 20.4% ± 4.4%, 1.6% ± 1.8%, and 47.7% ± 4.8% for each of the phases with an overall of 69.7% ± 0.5%. This is a slight improvement as compared with S10 removal efficiency (Fig. 2 S20(c)). Although the removal efficiencies for TKN and TP were not significantly improved by increasing circulation, the COD removal efficiency did by 10% compared with what was measured at the previous regime.

3.4. Scenario S30

At a 30% recirculation ratio scenario, the overall COD removal reached the 92% ± 1.7%. This compared with the previous regime (S20) increased the overall efficiency by 8% ($P < 0.05$, Table 3). The individual tank removal efficiencies for the anaerobic, anoxic, and oxic phase were 25.8% ± 3.0%, 29.8% ± 1.8% and 34.8% ± 2.7%, respectively (Fig. 2 S30(a)).

A slight increase (+1.7%) in TKN removal efficiency as compared with S20 was observed. The total TKN removal efficiency was 97.7% ± 0.4%. Anaerobic, anoxic, and oxic reactors removal efficiencies were 1.1% ± 0.8%, 94.6% ± 1.6%, and 2.0% ± 0.1%, respectively (Fig. 2 S30(b)). On the contrary, the TP removal efficiency significantly increased ($P < 0.05$, Table 3) by 5% over to at S20, reaching to 74.6% ± 0.5%. The removal efficiency from each phase was 18.6% ± 3.1%, 14.9% ± 2.1%, and 41.2% ± 1.0% observed in anaerobic, anoxic, and oxic reactors, respectively (Fig. 2 S30(c)).

3.5. Scenario S40

In this scenario, no further significant removal efficiencies increment for none of the measured parameters (COD, TKN, and TP). The removal efficiencies of the COD, TKN, and TP were 92.6% ± 0.2%, 97.2% ± 0.6%, and 74.9% ± 0.5%, respectively (Fig. 2 S40(a), S40(b), S40(c)).

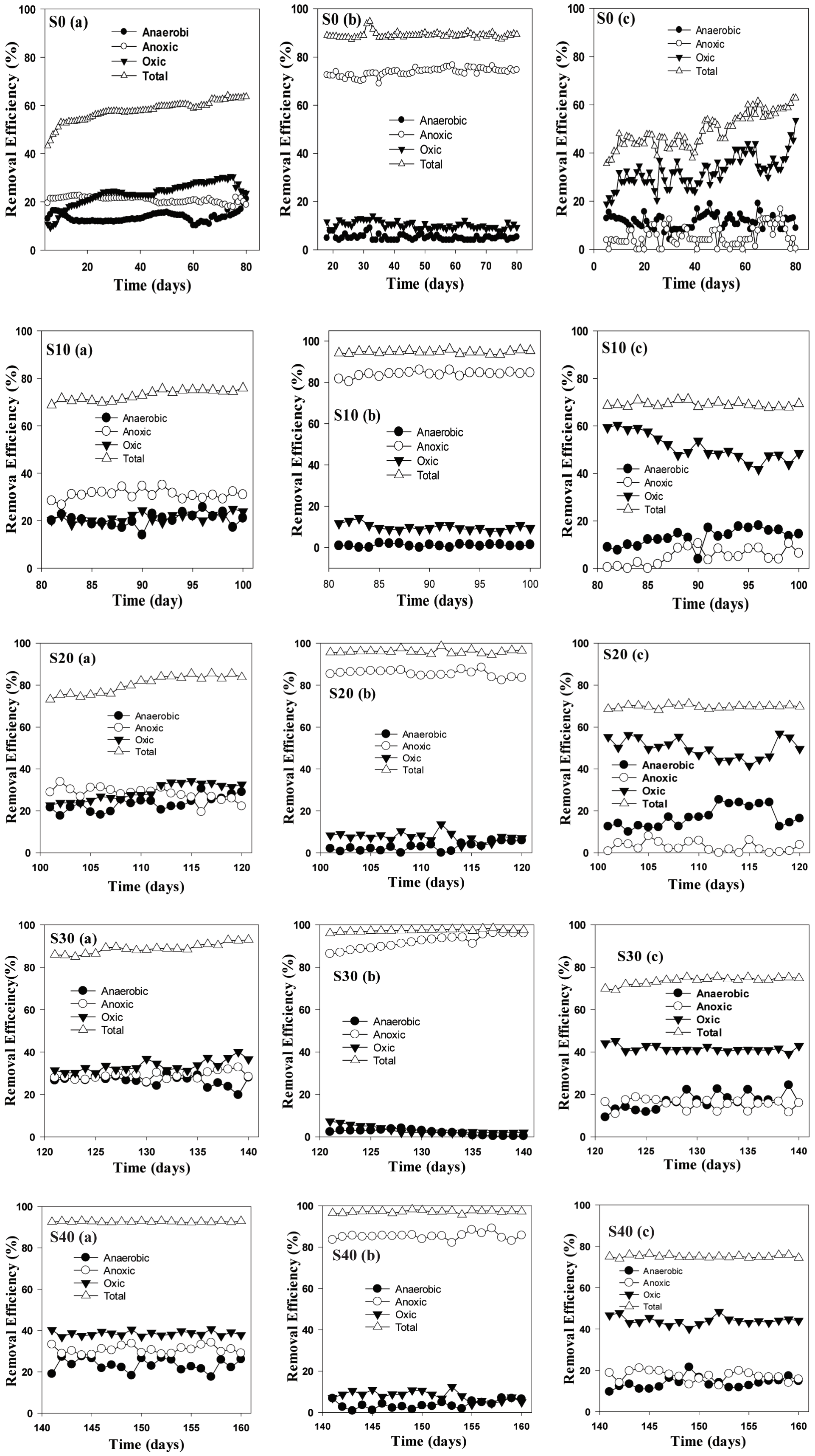

Fig. 2. Removal efficiencies of COD (a), TKN (b), and TP (c) at Scenario S0; Scenario S10, Scenario S20, Scenario S30, and Scenario S40.

3.6. Analysis of variance

The summary of the differences between the recirculation regimes is presented on Table 3. Single factor ANOVA highlighted the significant differences between the recirculation regimes S0–10, 10–20, and 20–30 ($P < 0.05$). No statistically significant difference was observed between the S30 and S40 (Table 3).

4. Discussion

Recirculation is the key variable in A2O systems as this allows the redistribution of the necessary compounds (electron donors) promoting carbon and nutrient wastewater treatment.

Specifically, recirculating PAOs from the secondary clarifier to the anaerobic section allows decomposition of the intracellular phosphate releasing phosphate and use of the released energy for organic matter uptake (mainly VFAs) to produce PHB. This was also the case at our study where P was reduced at all regimes, however, changes in the recirculation ratios showed that different regimes result to different removal efficiencies. Yin et al. [43] showed that 90 min were adequate for significant phosphate release and PHB production with TP concentration of 48 mg/L. Higher retention times were also tested on this study with no significant removal improvement. Lai et al. [40], using a similar setup with the one reported in this study, to also investigate the effect of HRT on treatment but could not exceed an efficiency of 63% and 71% for N and P, respectively, regardless HRT increase. The recirculation at this study was kept constant at 100% (influent:recirculation), while the sludge recirculation rate was 50% of the influent. The importance of the retention time in treatment processes is high, however, recirculation is also crucial. Hence, removal efficiency may be optimized by retention times but is also dictated by the rate of recirculation.

Optimizing recirculation indirectly promotes the availability of substrate (carbon) within the tank(s). The anaerobic phase at an A2O plays a vital role as carbon is mainly produced in it. Anaerobic fermentation is the process that provides with the necessary by-products that often account for the carbon source for both P-removal and denitrification of the produced from nitrification anions (nitrite and nitrate) [44]. With regards to the phosphorus, at this study P-uptake from the anoxic/aerobic stage is dictated by the anaerobic stage where phosphorous is released, acting as prerequisite for uptake at the aerobic stage.

Anoxic conditions significantly increased phosphate uptake due to the presence of high organic material (as COD). Uptake is unlikely at aerobic zones as thermodynamics cannot support such metabolic pathways in the absence of high organic matter. When uptake takes place at anoxic conditions the process is aligned with denitrification and careful design is required to eliminate microbial competition. There are four fundamental microbial populations that compete for substrate (PAOs, NOBs, AOBs, and other denitrifies), with NOBs and PAOs very likely to be outcompeted by AOBs [43,45].

Previous studies focused in reducing phosphorus in the absence of an anaerobic phase had ambiguous success. Patel et al. [46] investigated the feasibility of nutrients removal from municipal wastewater using a fluidized, lava-carrier-bed bioreactor (aerobic–anoxic, HRT of 2 h). In this study, the direct use of acetate to compensate the absence of the anaerobic part only highlighted the necessity of a low-cost anaerobic process at the P-removal process. The efficiency reported was similar to the one reported in our study in the absence of VFA-dosing.

An improved approach was presented by Sriwiriyarat et al. (2005) who used an integrated fixed film A2O system to treat wastewater at moderate temperature. This study highlighted the importance of solid retention time, and subsequently microbial growth, to the treatment of organic matter (COD) and nutrients. The reactor scheme on this study was similar with the one employed here (fixed film in anoxic and oxic zones), and achieved a removal efficiency of 95.1%, 75.0%, and 61.0% for COD, TKN, and P, respectively, efficiencies lower than those reported from our study. The recirculation at this study was kept nonoptimized and the results showed that higher denitrification could have achieved if more nitrate could had recycled [47]. The similar reactor regime and treatment functions imply that the higher, more cost efficient and sustainable nutrient removal efficiencies that are reported at our study are attributed to the optimized recirculation ratio (effluent and sludge). All the above show that treatment systems require optimization and recirculation is often the variable that is arbitrarily neglected.

These two streams (effluent and sludge recirculation) in this study were changing in parallel and the contribution of each one to treatment remains uncertain. Additional studies would be required to further improve A2O focusing mainly in differentiating these two streams. It is not certain whether it is the one or the other that affects the process efficiency the most, however, the fact that one is more beneficial than the other may lead to further optimization and subsequently cost reduction.

From the efficiency results it is observed that the C, N, and P removal at the final experimental days of each trial were consistent regardless the varying influent load. This implies that adaptation to fluctuating loads using a fixed film A2O is relatively rapid (<20 d). Different wastewater composition could theoretically lead to different effluent and sludge optimum ratios; the consistency in treatment among the final experimental days though makes us confident with regards the agreement in the recirculation optima regardless the varying composition of the influent (up to 30% difference for P, >10% for N).

5. Conclusion

A pilot scaled fixed film A2O system vividly demonstrated satisfactory biodegradation efficiency against nutrients (N and P) and carbon (COD) without any external carbon sourcing. Recirculation in these systems is essential for the redistribution of electron acceptors in the tanks. An optimum Q_{influent}:$Q_{\text{recirculation}}$ of 30% is advised for robust A2O treatment. Further increase will not provide with any further process improvement. The employment of the fixed film was a promising approach showing stability and robustness in removal performance for all flow redistribution regimes. Such quick trials (within weeks) would be required for sludge and effluent recirculation optimizations during commissioning and operation of such treatment plants.

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