



Performance of Novel Contact Stabilization Activated Sludge System on Domestic Wastewater Treatment¹ Desempeño de una nueva configuración del sistema de estabilización por contacto en el tratamiento de agua residual doméstica²

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Abstract

A pilot-scale study was conducted to evaluate a traditional contact stabilization activated sludge system (CSAS_C) and a modified CSAS (CSAS_M) treating domestic wastewater. The CSAS_C system was comprised of a contact reactor (CR), a stabilization reactor (SR) and a secondary settler (SS); the CSAS_M included a second CR, a second SS (CR₂ and SS₂), and a modified SR (SR_M) divided into four zones: an attached-suspended growth zone which allowed the system to reach an average sludge retention time close to 36 d and favored the occurrence of nitrification; an anoxic zone for denitrification occurrence; an aerated suspended growth zone with a high presence of organic carbon; and an additional aerated suspended growth zone with a high ammonia concentrations environment. The CSAS_C's removal efficiencies of chemical oxygen demand (COD) and total ammonia nitrogen (TAN) were respectively $94 \pm 4\%$ and $53 \pm 12\%$; whereas CSAS_M's efficiencies were $88 \pm 7\%$ for COD and $92 \pm 7\%$ for TAN. Concentrations of TAN and NO_3^- -N in the CSAS_C's final effluent were 14.3 ± 5.2 and $5.0 \pm 2.9 \text{ mg} \times \text{L}^{-1}$; and 4.8 ± 4.4 and $9.1 \pm 5.8 \text{ mg} \times \text{L}^{-1}$ in the CSAS_M's final effluent. Results demonstrated that the proposed configuration obtained higher nitrogen removal efficiencies than traditional CSAS.

Keywords

activated sludge; contact stabilization; organic carbon; nitrogen removal; domestic wastewater

Resumen

Usando una prueba a escala piloto se evaluó un sistema de estabilización por contacto convencional (CSAS_C) y uno modificado (CSAS_M), para el tratamiento de agua residual doméstica. El CSAS_C estuvo compuesto de un reactor de contacto (CR), un reactor de estabilización (SR) y un sedimentador secundario (SS); el CSAS_M incluyó la adición de un SR y un SS (CR₂ y SS₂) y la modificación del reactor de estabilización (SR_M), en cuatro zonas: una de crecimiento adherido-suspendido, que permitió alcanzar un tiempo de retención celular promedio cercano a 36 d y que beneficia el desarrollo de la nitrificación; una zona anóxica para el desarrollo de la denitrificación; una zona aireada de crecimiento suspendido, con un ambiente rico en materia orgánica carbonácea, y otra con un ambiente rico en nitrógeno amoniacal total (NAT). El CSAS_C presentó eficiencias de reducción de química de oxígeno (DQO) y NAT de $94 \pm 4\%$ y $53 \pm 12\%$ respectivamente; mientras que el CSAS_M presentó eficiencias del $88 \pm 7\%$, y de $92 \pm 7\%$, respectivamente. Las concentraciones promedio de NAT y N-NO_3^- en el efluente del CSAS_C fueron de $14,3 \pm 5,2$ y $5,0 \pm 2,9 \text{ mg} \times \text{L}^{-1}$, respectivamente, y para el CSAS_M fueron de $4,8 \pm 4,4$ y $9,1 \pm 5,8 \text{ mg} \times \text{L}^{-1}$, respectivamente. Estos resultados demostraron que la nueva configuración evaluada presentó mayores eficiencias de reducción de material nitrogenado.

Palabras clave

lodos activados; estabilización por contacto; materia orgánica carbonácea; remoción de nitrógeno; agua residual doméstica

Introduction

Municipal wastewater contains a variety of organic compounds of carbon and nitrogen. Nitrogen material is related not only to organic forms, but to inorganic forms, especially NH_4^+ -N. High nitrogen concentrations in wastewater are associated with eutrophication, which affects freshwater quality. In consequence, conventional wastewater treatment plants aim to reduce concentrations of such compounds in final effluent through secondary and tertiary treatment processes.

Contact Stabilization Activated Sludge system (CSAS) is a variation of the conventional activated sludge system (Figure 1a), where two aerated tanks and a secondary settler are used to remove carbonaceous material concentrations incoming with influent wastewater. The process begins in the Contact Reactor (CR), where influent wastewater is mixed with recirculation sludge from the Stabilization Reactor (SR) to conform the mixed liquor (ML). After a short hydraulic retention time (HRT) in the CR, the ML is conducted to the Secondary Settler (SS), where separation of clarified effluent and sludge occurs. Separated sludge is recirculated to SR to start the process again after a HRT of 2–8 h. The process' conceptual base is to optimize adsorption of carbonaceous material over the floc structure during CR's HRT, which ranges between 0.5–1.5 h, whereas SR is conceived with a longer HRT to metabolize in there substrates previously adhered to floc structure [1]–[3].

Different experiences have demonstrated the excellent performance of CSAS, with COD removal efficiencies almost always higher than 80% [4], [5], and even higher than 90% for BOD_5 [1]. CSAS has been also used as a high-load process for maximizing sludge production in domestic wastewater pretreatment, obtaining COD removal efficiencies of $66 \pm 5\%$ [6]. Nevertheless, even though nitrogen transformations are not intended to occur in CSAS, Alexander *et al.* [7] documented that a Sludge Retention Time (SRT) longer than 4d and high Recirculation Rates (R) favored nitrogen transformations in CSAS systems, whereas other papers have documented nitrification percentages in CSAS systems

of 25% [5], 70% [4], and 77% [2]. Furthermore, denitrification, ammonification, and denitrification can take place in small proportions in CSAS systems [2], [4]. Sludge Retention Time (SRT_c) is then a decisive variable to design and control CSAS systems. Eq. 1 shows the expression defined by Alexander *et al.* [7] for SRT estimation:

$$SRT = \frac{\text{mass of sludge in the process}}{\text{mass of sludged wasted per day}} = \frac{X_{CR}V_{CR} + X_{SR}V_{SR}}{X_{SR}Q_w} \quad (\text{Eq. 1})$$

Where:

X_{SR} : Volatile suspended solids in the sludge wasted from SR, $\text{mgVSS} \times \text{L}^{-1}$

Q_w : Waste flow ($\text{L} \cdot \text{d}^{-1}$)

The occurrence of nitrogen transformations in CSAS systems suggest that some modifications could be made to improve nitrogen removal without affecting organic carbon removal efficiencies. Anoxic zones with presence of high organic carbon concentrations can incentivize denitrification if there is an entrance of nitrate coming from nitrification in the SR, which can be stimulated through hybrid suspended-attached systems [8]-[10]. Currently, recent works in CSAS have proposed system modifications to improve phosphorus removal [11], but no research has been carried out for a nitrogen removal optimization. Considering this background, this study evaluated a $CSAS_C$ system and a $CSAS_M$ in order to evaluate nitrogen removal efficiencies.

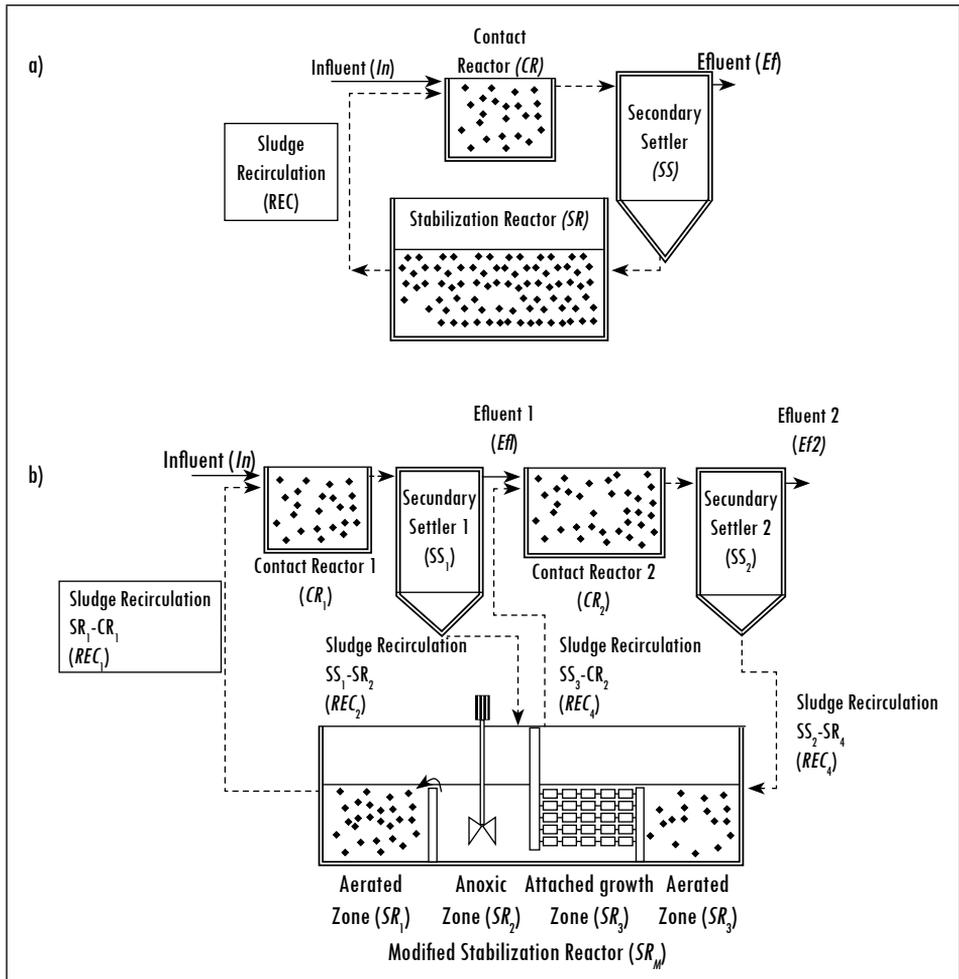
1. Materials and Methods

1.1. Experimental Unit

The CSAS system presented a typical configuration conformed by a contact reactor (CR), a stabilization reactor (SR), and a secondary settler (SS) (Figure 1a). The $CSAS_M$ (Figure 1b) was divided into two stages: The first stage (Stage 1) was primarily conceived for carbonaceous matter removal and included $CR_1 + (SS_1 + SR_{1+2})$, whereas the main purpose of the second stage (Stage 2) was nitrogen removal and included $CR_2 + (SS_2 + SR_{3+4})$. The stabilization reactor was a unique unit with different compartments that could be described as follows: i) SR_1 an aerated zone of suspended growth with a high presence of organic carbon; ii) SR_2 an anoxic zone which favored denitrification; iii) SR_3 an attached-suspended growth zone

which favored nitrification and denitrification; and finally, iv) SR_4 an additional aerated zone of suspended growth with a high ammonia concentrations measured as total ammonia nitrogen (TAN) for favored nitrification. The volumes of the treatment unit were 9.98 L for CR_1 , 36.68 L for CR_2 , 27.20 for SR_1 , 8.90 L for SR_2 , 8.75 for SR_3 , and 8.75L for SR_4 . Units were constructed on glass fiber and peristaltic pumps were used for recirculation lines. Aeration in CR_1 , CR_2 , SR_1 , and SR_4 was supplied with a blower and bubble diffusers.

Figure 1. (a) $CSAS_c$'s and (b) $CSAS_m$'s configuration



Source: author's own elaboration

Waste Sludge from real-scale “Aguas del Sur” wastewater treatment plant (WWTP) was used for the inoculation of the systems. CSAS_C start-up phase was performed during 10 d through progressive affluent flow increments, from 50% to 100%. Those increments were conditioned to COD removal efficiencies higher than 60%. Once CSAS_C operation period was completed, the CSAS_M start-up phase was begun. Inoculum acclimation and start-up phase were performed during 15d. After this period, SR₃₊₄ (separated from SR₁₊₂ through a division screen) and SS₂ were added as a second CSAS for CSAS_C's effluent post-treatment. After an additional 17 d, the division screen was removed, the four zones inside SR_M were established and the CSAS_M evaluation period was started. System's influent (*In*) was taken from “Aguas del Sur” WWTP, after screening and then conducted to a primary clarifier with a HRT of 1 h.

1.2. System Control and Evaluation

Samples from mixed liquors, Influent (*In*), and effluent of CSAS_C (*Ef*) and CSAS_M (*Ef*₂) were taken twice a week. COD, TAN, nitrates (NO₃⁻-N), phosphorus (PO₄³⁻-P), pH, and total and bicarbonate alkalinity were measured for influent characterization. Volatile suspended solids (VSSML), pH, and dissolved oxygen (DO) were measured in mixed liquors of CR and SR in CSAS_C, and CR₁, CR₂, SR₁, SR₂, SR₃, and SR₄ in CSAS_M. In order to operate CSAS_C and CSAS_M, VSSLM, DO, pH, temperature, food-microorganisms ratio (F/M), and SRT were monitored. COD and TAN removal efficiencies were estimated from influent and effluents concentrations, where NO₃⁻-N and alkalinity were also measured. All parameters were determined as indicated by [12].

Operational conditions evaluated in CSAS_C and CSAS_M during the operation were chosen from previous studies in CSAS systems. A SRT range between 6-10 d was chosen to secure nitrification. HRT_{CR} of 0.84 h, HRT_{SR} of 4.10 h, VSSML_{CR} of 1000 mg×L⁻¹, and VSSML_{SR} of 2000 mg×L⁻¹, DO concentration of 4.0 mg×L⁻¹ [2], [5], [7]. Wasted sludge was taken from SR and SR₁ in CSAS_C and CSAS_M respectively. Sludge retention time for CSAS_C (SRT_C) was evaluated according to Eq. 2, according to solids flow in the CSAS_M, although a global SRT (SRT_{M-G}) was totalized as shown before in Eq. 1; an internal SRT was also established for each stage. For Stage 1, suspended biomass in CR₁, SR₁, and SR₂ and sludge wasted from SR₁ define the SRT_{M-S1} as expressed in Eq. 2.

$$TRC_{M-S1} = \frac{\text{Biomass in Stage 1}}{\text{Biomass leaving Stage 1}} = \frac{V_{CR1}X_{CR1} + V_{SR1}X_{SR1} + V_{SR2}X_{SR2}}{Q_{EF1}X_{EF1} + Q_{WSR1}X_{SR1} + S_1} \quad (\text{Eq. 2})$$

Where:

- S_1 : biomass sampled from Stage 1
 S_I : $Q_{M, CR1} * X_{CR1} + Q_{M, SR1} * X_{SR1} + Q_{M, SR2} * X_{SR2}$
 Q_M : Q_{sampled} in each reactor ($L \times d^{-1}$)
 $Q_{w, SR1}$: Sludge waste flow from SR_1 ($L \times d^{-1}$)

For Stage 2 suspended biomass in CR_2 , SR_3 , and SR_4 and attached biomass in SR_3 were considered to define SRT_{M-S2} (Eq. 3). According to $CSAS_M$ configuration, of SRT_M was defined as presented in Eq. 3, by considering attached and suspended biomass. Attached biomass was estimated using the mathematical model of Ritmann and McCarty [13] for attached biomass growth ($aVJYb_t^{-1}$), which has been employed in different works related with attached-suspended reactors [14], [15], [10]. Kinetic parameters registered in Table 1 and simplified expressions proposed by Fouad and Barghava [15] were used to estimate $aVJYb_t^{-1}$. According to low C/N conditions in SR_3 , ammonia oxidizing bacteria (AOB) predominated in attached growth and consequently, kinetic constants from AOB were employed to estimate $aVJYb_t^{-1}$. Values in Table 1 were taken from references where a particular estimation of each constant was made, similar physicochemical conditions to SR_3 predominated, and low density polyurethane was employed for attached growth. Finally, for the estimation of SRT_{M-S2} it was considered that sludge flow from SR_3 to SR_4 constituted a sludge waste from Stage 2. Attached biomass concentration (X_p) was estimated by separating it from media using a Stomacher 400 mL Bagmixer-400W Interscience®, at 7 strokes for 60 s. Separated biomass was diluted in distilled water and VSS were measured finding a value of $7238 \text{ mgVSS} \times L^{-1}$.

$$\begin{aligned}
 TRC_{M-S2} &= \frac{\text{Biomass in } S_2}{\text{Biomass leaving } S_2} = \frac{\text{Suspended biomass} + \text{attached biomass}}{\text{Biomass leaving } S_2} \\
 &= \frac{V_{CR2} X_{CR2} + V_{SR3} X_{SR3} + V_{SR4} X_{SR4} + aVJ \frac{Y}{b_t}}{Q_{EF2} X_{EF2} + Q_{w, SR3} X_{SR3} + S_2} \quad (\text{Eq. 3})
 \end{aligned}$$

Where:

- s_2 : biomass sampled from Stage 2
 s_2 : $(Q_{MCR2} \times X_{CR2}) + (Q_{MSR3} \times X_{SR3}) + (Q_{MSR4} \times X_{SR4})$
 $Q_{w, SR3}$: Sludge flow from SR_3 to SR_4 ($L \cdot d^{-1}$)
 $aVJYb_t^{-1}$: Attached biomass expression

Table 1. Kinetic and stoichiometric parameters selected for $aVJYb_1^{-1}$ estimation

Parameter	Notation	Value	Units	References
TAN half saturation coefficient*	K_{TAN}	1.47	mgTAN \times L ⁻¹	Grady <i>et al.</i> [16]
Maximum specific rate of TAN utilization	k_{TAN}	3.80	d ⁻¹	Lin [17]
Yield coefficient	Y_{AOB}	0.33	mgVSS \times (mgNH ₄ ⁺ -N) ⁻¹	Ritmann and McCarty [13]
Specific decay rate**	k_d	0.15	d ⁻¹	Spanjers and Vanrolleghem [18]
Specific shear loss rates	b_s	1x10 ⁻⁴	d ⁻¹	Lin [17]
Molecular diffusion coefficient in the biofilm	D_f	1.382	cm ² .d ⁻¹	Lin [17]
Molecular diffusion coefficient in water	D_w	1.300	cm ² .d ⁻¹	Ritmann and Manem [14]
Biofilm layer thickness	L (cm)	0.0082	cm	Lin [17]
Polyurethane specific surface area	A	11.2	cm ⁻¹	Feng <i>et al.</i> [19]

(*)(**) Temperature correction was applied. Temperature in SR₃ presented a mean value of 27.5 °C. ^(*) $\Theta = 1,053$ [20].

K_{TAN} in reference: 1.0 mgTAN \times L⁻¹ (20 °C). ^(**) $\Theta = 1.04$ [20]. k_d in Reference, 0.11 d⁻¹ (20 °C).

Source: author's own elaboration

2. Results

2.1. Influent Characterization

After primary clarification, influent was transported to the evaluated systems. Previous research has demonstrated that primary clarifiers do not affect influent nitrogen concentrations and have a positive influence on CSAS's performance because they function as a barrier to fats, oils, and surfactants that affect secondary sludge quality [21]. Influent characteristics are presented in Table 2. Influent variation was conditioned by wastewater production dynamic in "Agua del Sur" WWTP. CSAS_M's influent was more concentrated than CSAS_C's, which was influenced by a rainy season. Measured values for both CSAS_C and CSAS_M were according to typical ranges of wastewater produced in Santiago de Cali, and guaranteed carbonaceous organic matter, nutrients, and alkalinity availability for biological processes. No influence of wastewater quality variations was detected

in the performance of both, CSAS_C and CSAS_M, and no statistical differences were noted in influent TAN concentration.

Table 2. Influent characterization

Parameter	Units	Measured Values	
		CSAS	CSAS _M
COD	mg×L ⁻¹	222.8 ± 73.7	341.2 ± 122.6
BOD ₅	mg×L ⁻¹	124.7 ± 71.5	192.1 ± 56.5
TAN	mg×L ⁻¹	34.7 ± 6.6	48.9 ± 9.0
NO ₃ ⁻ -N	mg×L ⁻¹	0.21 ± 0.30	1.1 ± 0.8
PO ₄ ³⁻ -P	mg×L ⁻¹	5.7 ± 1.1	9.3 ± 1.5
Bicarbonatic alkalinity	mgCaCO ₃ ×L ⁻¹	119.7 ± 24.2	203.0 ± 36.7
Total alkalinity	mgCaCO ₃ ×L ⁻¹	160.0 ± 31.5	303.9 ± 32.0
TSS	mg×L ⁻¹	51.5 ± 19.7	80.8 ± 63.0
pH	unid	6.30 a 7.20	6.45 - 7.54

Source: author's own elaboration

2.2. System Performance and Nitrogen Removal

Operational conditions in CSAS_C and CSAS_M are registered in Table 3. Obtained values were according referenced values for CSAS systems where nitrification took place. Additionally, temperature and pH ranges were optimum for nitrification occurrence (pH: 7.5 - 8.0 units, T: 28-36 °C [22]).

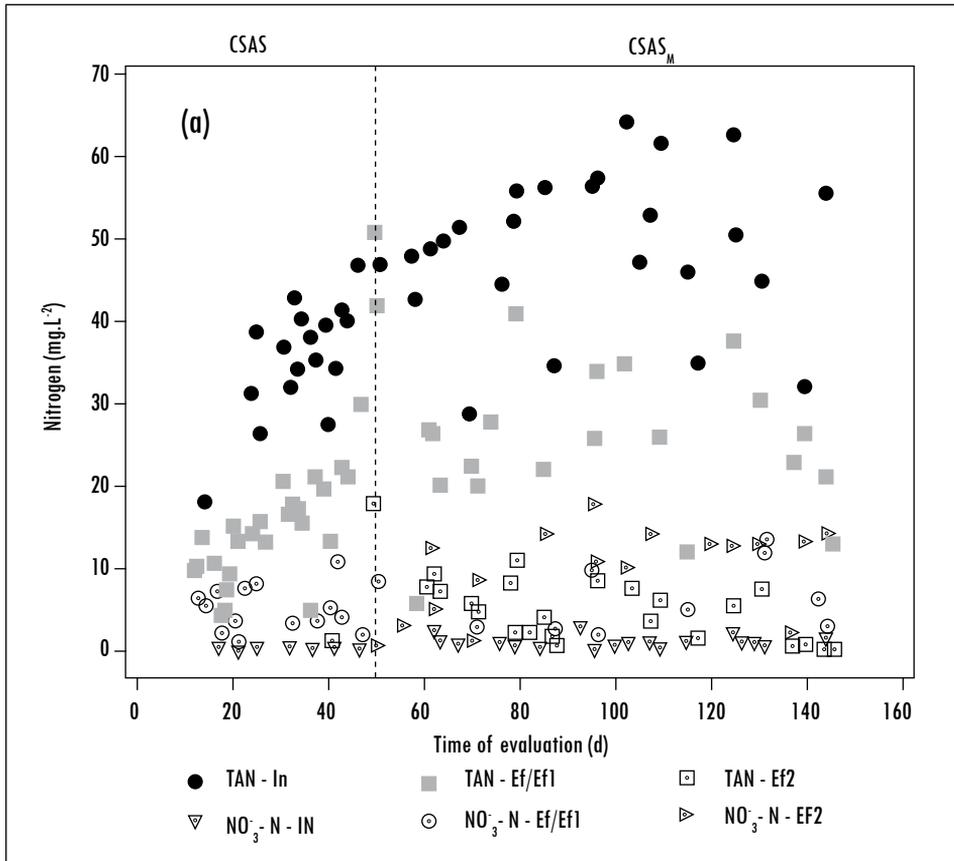
Table 3. Operational conditions

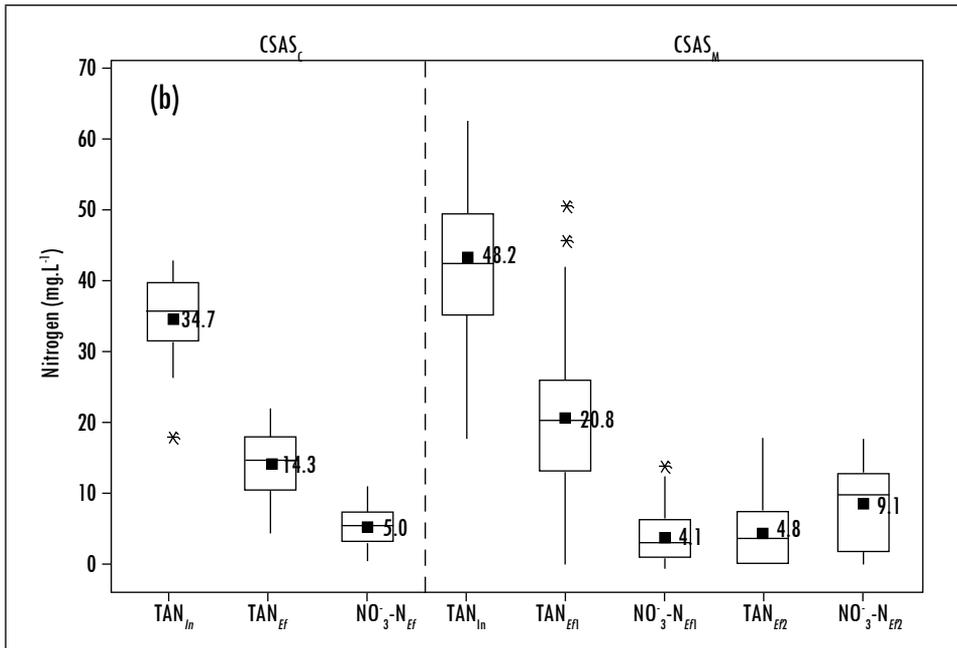
System	Reactor	HRT (h)	pH (unit)	T (°C)	VSSML (mg×L ⁻¹)	DO (mg×L ⁻¹)
CSAS REC = 100%	CR	0.84	7.1-7.8	28.2±2.0	1498 ± 350	3.2±1.2
	SR	4.02	6.7-7.6	28.3±1.9	3588 ± 726	2.1±1.4
CSAS _M REC ₁ = 51% REC ₂ = 50% REC ₃ = 98% REC ₄ = 100%	CR ₁	0.83	6.2-8.1	26.5±1.5	1243 ±412	3.0±1.7
	CR ₂	3.03	5.5-7.7	26.2±1.7	1393 ±523	3.3±1.6
	SR ₁	4.43	5.7-7.7	26.6±1.7	2448 ±1160	3.1±1.7
	SR ₂	1.45	5.8-7.7	26.6±1.7	2752 ±1083	0.8±1.1
	SR ₃	0.73	5.8-7.8	26.6±1.7	2771 ±1009	1.9±1.3
	SR ₄	0.73	5.8-7.8	26.6±1.7	2638 ±1025	1.9±1.2

Source: author's own elaboration

TAN and NO_3^- -N concentrations in final effluent of CSAS_C (E_f) were $14.3 \pm 5.2 \text{ mgTAN} \times \text{L}^{-1}$ and $5.0 \pm 2.9 \text{ mgNO}_3^- \text{-N} \times \text{L}^{-1}$, whereas concentrations of in CSAS_M 's final effluent (E_f) were $4.8 \pm 4.4 \text{ mgTAN} \times \text{L}^{-1}$ and $9.1 \pm 5.8 \text{ mgNO}_3^- \text{-N} \times \text{L}^{-1}$, respectively. Figure 2 presents the variation in the nitrogen compounds concentrations of the final effluent. TAN removal efficiencies were respectively $53 \pm 12\%$ and $92 \pm 7\%$ for traditional (CSAS_C) and modified (CSAS_M) systems.

Figure 2. Nitrogen variation in CSAS_C and CSAS_M





Source: author's own elaboration

TAN removal efficiencies observed in the traditional system (CSAS_C) were similar to those previously reported in [1], [4]. Both TAN removal efficiencies and NO₃⁻-N concentrations in the final effluent evidenced that nitrification was the main TAN transformation process. Environmental conditions in the contact reactor (CR) and the stabilization reactor (SR) support this idea as an aerobic environment predominated (CR: 3.2 ± 1.2 mgDO \times L⁻¹ and SR: 2.1 ± 1.4 mgDO \times L⁻¹), inorganic carbon presence supported by total and bicarbonate alkalinity concentrations in influent, and a SRT high enough to enable nitrifier organism growth at process' temperatures. Even when NO₃⁻-N concentrations in CSAS_C's final effluent (Ef) were low, processes of NO₃⁻-N removal like denitrification could have occurred only in low rates because the environmental conditions in CR and SR were predominantly aerobic, however, a possible presence of anoxic microzones and a complete anoxic environment in the bottom of the SS could have promoted incipient denitrification.

The higher TAN removal efficiencies exhibited by CSAS_M were related to Stage 2 performance. The establishment of high SRT_{M-S2} was a consequence of attached growth in SR₃, which possibly favored the presence of nitrifiers and distribution in CSAS_M. The measured SRT_{M-S2} of 20.9 ± 6.7 d which increased the SRT_C values up to 36.2 ± 14.2 d are coincident with those reported for

attached-suspended growth reactors to favor nitrification performance [8], [23], [24]. The high nitrification rates compared with low NO_3^- -N concentrations in CSAS_M's final effluent suggest that processes of NO_3^- -N removal actually took place in CSAS_M at a considerable rate, which is consequent with SR_2 's conditions. Low DO concentrations ($0.7 \pm 1.0 \text{ mg} \times \text{L}^{-1}$) in the anoxic compartment (SR_2) and the permanent entrance of carbonaceous organic matter incoming, with recirculation from SS_1 and NO_3^- -N from the attached growth compartment (SR_3), suggest that the main process of NO_3^- -N removal was denitrification.

An incipient denitrification took place in the bottom of CSAS_M's SS_2 . Some sludge resuspension events are evidence of denitrification in the aforementioned zone. Presence of carbonaceous matter from endogenous metabolism and NO_3^- -N produced in Stage 2, as well as DO absence were conditions that promoted denitrification. Small N_2 bubbles produced by denitrification could have risen from the bottom of SS_2 , thus explaining sludge resuspension events.

Eventual NO_3^- -N concentrations below $2 \text{ mg} \times \text{L}^{-1}$ measured in the final effluent (Ef_2) are evidence that CSAS_M's conditions can be adjusted in order to optimize denitrification process limited by a high R value in REC_3 (98%). Even when NO_3^- -N were produced in SR_3 and SR_4 , the high R value in REC_3 made that a high NO_3^- -N flow to the CR_2 limited its availability in SR_2 for denitrification. Whereas denitrification was affected due to the high R value in REC_3 , this condition had a positive influence in Stage 2 performance as it controlled biomass waste, determining the $\text{SRT}_{\text{M-S2}}$ ($20.9 \pm 6.7 \text{ d}$). This condition promoted nitrification and high VSSML concentrations that guaranteed the system's operational stability. Results suggest that R value could be adjusted in order to promote denitrification in SR_2 and secure the system's operational stability

Conclusions

TAN removal efficiencies observed for the modified CSAS system (CSAS_M) were significantly higher ($92 \pm 7\%$) compared to traditional CSAS system (CSAS_C) and NO_3^- -N concentrations in the final effluent were considerably low ($9.1 \pm 5.8 \text{ mg} \times \text{L}^{-1}$). This behavior suggests that the proposed modifications improved nitrogen removal processes in the CSAS_M. Operational conditions established in both CSAS_C and CSAS_M indicated that nitrification was the predominant TAN transformation process. Stage 2 helped CSAS_M to reach higher nitrification efficiencies in comparison with CSAS, where the main nitrogen removal process in Stage 1 was denitrification, which took place especially in the anoxic compartment (SR_2) where adequate environmental conditions for

its occurrence were established. Finally, the R value in REC_3 must be carefully evaluated in order to allow an abundant flow of NO_3^- -N to SR_2 by the time that operational stability concerning VSSML must be also guaranteed.

A strong relationship between REC_3 and $\text{SRT}_{\text{M-S2}}$ was found as REC_3 controlled biomass waste from Stage 2. The R value of 98% for REC_3 promoted a high $\text{SRT}_{\text{M-S2}}$ average of 20.9-6.7 d and secured the system's operational stability in terms of SSVML concentrations, with values of $1243 \pm 412 \text{ mg} \times \text{L}^{-1}$ in CR_1 , $1393 \pm 523 \text{ mg} \times \text{L}^{-1}$ in CR_2 and around $2500 \text{ mg} \times \text{L}^{-1}$ in SR_M 's compartments.

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