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Municipal wastewater treatment by a coupled fixed biomass oxic-anoxic system

E.R. Guzmán Gorrochotegui[a], M.C. Carreño de León[a], M.J. Solache-Ríos[b], C. Fall[c], N. Flores-Alamo[a,*]

[a]*Tecnológico Nacional de México/Instituto Tecnológico de Toluca, Av. Tecnológico S/N Col. Agrícola Bellavista, C.P. 52149, Metepec, México, Tel. + (52) (722) 2 08 72 00; emails: nfloresa@toluca.tecnm.mx (N. Flores-Alamo), rgorrochotegui@gmail.com (E.R. Guzmán Gorrochotegui), mcarcarleon@yahoo.com.mx (M.C. Carreño de León)*
[b]*Departamento de Química, Instituto Nacional de Investigaciones Nucleares, Carretera México-Toluca S/N, La Marquesa, Ocoyoacac, Estado de México C.P. 52750, México, email: marcos.solache@inin.gob.mx (M. Solache-Ríos)*
[c]*Instituto Interamericano de Tecnología y Ciencias del Agua, Facultad de Ingeniería, Universidad Autónoma del Estado de México, Apdo. Postal 367, Toluca, Estado de México, C.P 50091, México, email: c-fa-ll@hotmail.com (C. Fall)*

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ABSTRACT

A hybrid system of a sequential oxic-anoxic bioreactor and a fluidized immobilized cell carbon oxidation with Kaldnes K1 as supporting material and activated carbon were used to evaluate the removal efficiencies for biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) from domestic wastewater collected at the entrance of the biological reactor from a municipal wastewater treatment plant. The laboratory-scale hybrid biofilm treatment system was fabricated with 5 mm acrylic sheets, the effective volume of the system was 31.6 L. The operation of the treatment system was carried out with an optimal hydraulic retention time of 31.33 h and flow rate of 15 mL/min for 170 d at a mean temperature of 20°C, the pH of the wastewater was between 6.54 and 7.50, and a variable organic loading rate from 0.077 to 1.13 kg BOD_5/(m^3 d) depending on the daily influent wastewater to the wastewater treatment plant. The means removal efficiencies in the 170 d of operation achieved for BOD_5, COD, TN, TP were between 84%–99%, 80%–97%, 24%–97% and 21%–94%, respectively.

Keywords: Biological; Reactor; Kaldnes; Wastewater; Oxic; Anoxic

1. Introduction

Municipal wastewater is composed mainly of organic matter, although inorganic matter can also be present. Various treatments are used to remove organic and inorganic substances from wastewater, such as physical, chemical, and biological treatments. Biological processes have been used throughout the world to treat municipal wastewater; although they are economical and efficient in the removal of organic matter, these processes generate large amounts of by-products (for example, sewage sludge) [1].

Among the biological treatments, adherent growth systems such as biofilms have been used due to their low demand for space, less susceptibility to temperature fluctuations and low energy consumption. In these treatments, the simultaneous growth of flocs and the attached growth of microbial communities (biofilms) to inert support take place. In addition, they have higher removal efficiencies of organic and inorganic matter than the conventional activated sludge systems, due to the increase of the solid retention times and the microbial population capable of increasing the rate of contaminants degradation [2]. Bonded

* Corresponding author.

biomass instead of suspended biomass allows more compact reactors and provides easier separation of biosolids from the treated effluents.

In the reactors with attached biomass, microorganisms grow on an inert material, which could be synthetic (plastics, foams, ceramics, among others), or natural (mainly rocks, coal, basalt, among others). Biofilm formation occurs after initial cell adhesion to the surface of the support material then leads to the accumulation of bacteria and the production of extracellular polymeric substances, that adheres and protect bacteria from environmental stress and facilitate communication between them through biochemical signals [3]. Bacteria grow and die in the biomass, dead bacteria are removed from the biomass by the action of the aqueous phase, while the fixed bacteria adhered to the solid medium are very stable and active.

Biofilm systems have been used successfully in the treatment of synthetic, domestic and industrial residual wastewaters [4], because they show the following advantages: (i) less complex operation in comparison with the activated sludge systems, (ii) the ability to increase biological reaction rates through the accumulation of active biomass, longer microbial retention time, and growth of slow-growing microorganisms such as nitrifying bacteria and (iii) adhered biomass has high resistance to toxic compounds [5].

Biofilm systems, submerged aerobic biological filters, rotating biological contactors or bio disks, have been proposed in recent decades as an alternative for wastewater treatment rather than conventional biological processes. The type of reactor configuration and its operation play important roles on the effectiveness of the process. Recent studies have focused on the use of hybrid systems that combine aerobic and anaerobic processes integrated into moving bed biofilm reactors (MBBR) and fixed bed bioreactors (FBBR) [6] for the treatment of domestic wastewater. The main advantage of combined processes is a higher biodegradation rate.

Different configurations have been tested, for example, Luo et al. [6] investigated the performance of a hybrid system of a moving bed biofilm reactor and membrane bioreactor (MBBR-MBR), they found that adding a membrane bioreactor (MBR) to the system can improve the removal of micropollutants such as ketoprofen, carbamazepine, primidone, bisphenol A, and estriol from 25.5% to 99.5% and also mitigate the fouling of the membrane. Shao et al. [7] tested a fixed-bed bioreactor operated in sequential batch mode (FBBR-RSB); the system was efficient to eliminate chemical oxygen demand (COD) and ammonium from the wastewater, the removal was around 99% for ammonium and 92%–98% for COD. Chatterejee et al. [8] studied a system with three reactors: an upflow anaerobic reactor (UASB) followed by an MBBR and a rope bed biofilm reactor (RBBR); the hybrid system achieved a COD and total nitrogen removal of 99% and 89% respectively.

Tawfik et al. [9] used an anaerobic up-flow anaerobic reactor (UASB) and a moving bed biofilm reactor (MBBR) with a temperature from 22°C to 35°C, for the treatment of wastewater taken from a sewage network by monitoring the removal of total COD, colloidal COD and soluble COD. The experimental phase lasted 290 d, the first 38 d were considered the start-up phase, and the following days were the adaptation phase. The volume of the reactors was 10 L for the RAFA reactor and 8 L for the RBLM reactor. Reductions of 80%–86% for total COD, 50%–73% for colloidal COD and 20%–55% for soluble COD were obtained.

On the other hand, Khan et al. [10] monitored the efficiency of a FBBR with a stone support medium followed by a filter of sand to treat domestic wastewater, during different time intervals (12–48 h). The results revealed that the efficiency of MBBR improves by increasing the treatment time. The elimination of biochemical oxygen demand (BOD_5), COD and turbidity were 89.67%, 89.62% and 99.84%, respectively, when the treatment was performed with the MBBR and the filter of sand; 97.12%, 97.15% and 100% reduction for BOD_5, COD, and turbidity were achieved. Finally, Andreottola et al. [11] used a real scale system of rotating biological contactors and an MBBR (RBC-MBBR), achieving removals of carbon and nitrogen of 73% and 72%, respectively at a lower temperature than 8°C. In addition, they found that the hydraulic retention time (HRT) affects the removal of BOD_5 in the MBBR and suggest that the HRT should be longer than 5 h. Jaafari et al. [12] studied the performance of three moving bed biofilm reactors (MBBRs) operated in series as anaerobic anoxic and oxic reactor respectively to remove COD, total nitrogen (TN) and total phosphorus (TP) from synthetic wastewater with an efficiency removal of 91%, 82% and 71% respectively. Jaafari et al. [13] conducted a study in a pilot plant (Phoredox reactor) with moving media Kaldnes K3 to remove COD at different concentrations (500, 400 and 300 mg/L), 95.5% removal efficiencies for COD at an initial concentration of 400 mg/L were reached in 8 h, BOD_5 was 94.9%, and the maximum TP removal of 96.5%.

Therefore, the aim of this work was to evaluate a hybrid biofilm system integrated by a sequential oxic and anoxic bioreactor and fluidized immobilized cell carbon oxidation (SOABR-FICCO) reactors operating oxic-anoxic conditions for effective elimination of dissolved organic and inorganic matter expressed as BOD_5, COD, TN and TP present in real municipal wastewater, as well as the characterization of the microbial consortium developed as biofilms on the supporting material Kaldnes K1, the experiments was carried out for three retention times and the optimal operation time was reported here. The system was continuously operated for 170 d using wastewater (sampled at different times as required).

2. Materials and methods

2.1. Biofilm reactor

The laboratory-scale hybrid biofilm treatment system was fabricated with some modifications of the design by Mannacharaju et al. [14], the system was manufactured with 5 mm acrylic sheets, with a rectangular base and interconnections of 12.7 mm of PVC tubes. The system has a SOABR connected to a reactor FICCO. The effective volume of the system was 31.6 L, a flow rate of 15 mL/min and a HRT of 31.33 h, which allowed the fluidization of the supporting material.

The SOABR was made up of three chambers of 24 cm × 8 cm × 36 cm (length, width, height). The supporting material was placed inside each chamber; a screen with small weirs was installed between each chamber to allow the flow of wastewater. At the bottom of each reactor chamber a valve was placed to drain the sludge produced and a plastic mesh at a height of 6 cm from the bottom was placed to prevent the supporting materials to be dragged to the sludge purge. The FICCO has a rectangular shape with a hopper-shaped bottom; its dimensions were: 40 cm × 31 cm × 28.4 cm, it has two compartments, one for the activated carbon and the other for the supporting material (Fig. 1).

The activated carbon zone was equipped with air diffusers to supply oxygen to the microbial mass for biological activity, as well as to fluidize the activated carbon. The compartment with the supporting material served to degrade some of the water contaminants that persist after they passed through the SOABR. Air was supplied using two AQUARIUM RS-180 model air pumps with an aeration rate of 2.5 L/min and a HRT of 31.33 h. The dissolved oxygen concentrations varied throughout the operating cycle, around 0.10–4.65 mg/L for the SOABR and 3.65–4.87 mg/L for the FICCO. The pH and temperature remained within the ranges of 6.54°C–7.50°C ± 1.20°C and 18.5°C–21.4°C ± 2.45°C, respectively.

2.2. Supporting material

The supporting material selected for the growth of the biofilm was Kaldnes K1, which is a commercial material, made of polyethylene (density 0.95 g/cm^3) and resistant to degradation (useful life of 10 y) with the cylindrical shape of 9.1 mm of diameter and 7.2 mm of length. Commercial plastic supports have shown long life in operating water treatment systems without showing any degradation [15]. This type of material has been used in various works involving biofilm reactors with good results on the formation of the biofilm and on the reduction of contaminants such as BOD_5 and COD [10,15]. Ødegaard et al. [16], recommend that the filling fraction of the total volume of the reactor should be between 30% and 70%. The filling percentage was 40% for the SOABR and 25% for FICCO in the system used in this work and the total filling fraction was 65% for the complete system.

2.3. Start-up of SOABR-FICCO and selection the optimal HRT

During the start-up of SOABR, a mixture of wastewater and activated sludge (6:1) sampled at a biological reactor from a municipal wastewater treatment plant (WWTP) at Toluca, State of Mexico was used to feed in continuously mode the SOABR and improve biofilm development on the surface of the Kaldnes K1 support. This process of biofilm development was monitored continuously util it maintained almost the same thickness and then started the preoperational experiments to removed COD, BOD_5, TN and TP using wastewater sampled from the influent to activated sludge reactor at WWTP and supplied to SOABR-FICCO using three different HRTs (47.0, 31.33 and 23.5 h) calculated using an effective volume reactor (without supporting media) to select the optimal operation conditions.

2.4. Analytical methods

The wastewater influent was collected at the entrance of the activated sludge tank of the local municipal wastewater treatment plant (WWTP) at Toluca, State of Mexico, 152 L per week of this water were stirrer with a mechanical one during the experiments. All samples were stored at 2°C before the analysis. The main parameters analysed were based on current Mexican Standards: pH, dissolved oxygen (DO), chemical oxygen demand (NMX-AA-030-SCFI-2001), biochemical oxygen demand (NMX-AA-028-SCFI-2001), total nitrogen (NMX-AA-026-SCFI-2001), total phosphorus (NMX-AA-029-SCFI-2001), and for solids and salts dissolved the NMX-AA-034-SCFI-2015 was applied,

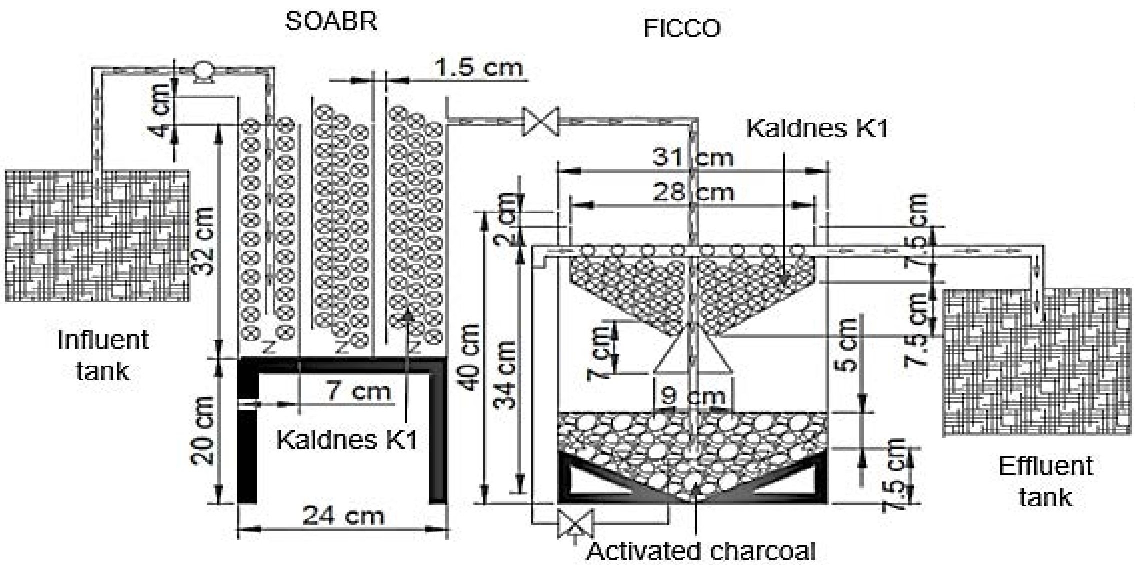

Fig. 1. Dimensions of the SOABR-FICCO system.

total solids (TS), total volatile solids (TVS), total dissolved solids (TDS) and total suspended solids (TSS). These are in total agreement with the Standard Methods for the Examination of Water and Wastewater of APHA [17]. Three samples of the influent and effluent water were collected weekly, and the average values of each parameter were calculated. The physicochemical analyses for the chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), total nitrogen (TN), total phosphorus (TP), oxygen and pH were performed according to standard methods for wastewater analysis.

2.5. Characterization of the biofilm

A qualitative analysis was performed to identify the presence of some type of filamentous microorganism. This was done by microscopic examination of the biofilms (immersion in oil and direct illumination at 100x), the morphological characteristics and staining reactions of each microorganism were performed to elucidate the phenotypic variations.

The analysis of the microfauna of wastewater treatment plants is very important because it has a decisive influence on the performance of the WWTP. The microstructure of the biofilms generated on the supporting materials was observed by scanning electron microscopy (SEM) analysis [18].

Samples of biofilms for SEM analysis were collected in the weeks 1, 12 and 24 from each chamber of the SOABR-FICCO system, considering the initial, intermediate and final stages of the operation system. They were placed in an incubator at room temperature (25°C to 30°C) from 10 to 15 d. During that time the biofilm was detached from the supporting medium, forming sheets of dry sludge (2–3 mm). The samples were covered with gold and examined (Hitachi S-4800, Japan) under an accelerating voltage of 15 kV, at a temperature and pressure of 20°C and 2.60×10^3 Pa. The images were taken at a magnification of 2,000X [11,18].

3. Results and discussion

The basic water quality parameters of the wastewater taken from the municipal wastewater treatment plant are shown in Table 1. The samples were taken at the entrance of the activated sludge reactor.

3.1. Development and characterization of the biofilm

Fig. 2 shows the growth of the biofilm on the Kaldnes K1 material during the conditioning stage of the biological reactor. The quantity of biofilm developed on the external surfaces of the Kaldnes was lower than in the internal surface because the first one is subjected to higher turbulence and abrasion, wastewater moves within each compartment of the reactors and promotes friction between the supporting material devices.

Dong et al. [19], reported that, the biofilm reaches steady state in the system from 25 to 35 d. Kriklavova and Lederer [20] reported biofilms adaptation times of 69 and 53 d for nanofiber and Kaldnes K3 supporting materials, respectively. Mannacharaju et al. [14], observed the formation of the biofilm on day 20 and was stable up to the day 170; they used cylindrical plastic supporting materials in a sequential oxic-anoxic biofilm reactor fed with municipal wastewater.

The formation of the biofilm depends on the source of the wastewater, and the presence of organic matter and oxygen. Proteins and polysaccharides are the main biochemical components and frequently the biofilm is visible after 5 d [21]. If there is enough nutrients and oxygen at the beginning of the adherence stage, then the microorganisms grow rapidly increasing the thickness of the biofilm (Fig. 2); as the microbial population grows, oxygen and nutrients are consumed, however, oxygen does not penetrate the entire thickness of the biofilm, so there is an anaerobic environment inside (this anaerobic environment is helpful on the removal of TP). In this work, the maturity of the biofilm was reached on the day 25, when the biofilm layer completely covered the internal surface area of the supporting material, these results agree with those reported by Mannacharaju et al. [14] and Dong et al. [19].

3.2. Gram stain

Qualitative microscopic observations by means of Gram staining were carried out with the biofilms obtained from the supporting materials. High number of microscopic life forms were observed (Fig. 3).

The microscopic identification of the biofilm shows a heterogeneous population of Gram-negative microorganisms such as coccus and bacillus and Gram positive and Gram-negative filamentous microorganisms (Fig. 3). Among the species found are bacteria, microalgae (*Anabaena* sp., *Oscillatoria limosa*), diatoms (*Nitzschia* sp.) and ciliated protozoa (*Opercularia* sp.). They were constantly changing depending on the composition of the wastewater and environmental conditions. In the SOABR, filamentous microorganisms were observed in the lower part of the three chambers (*Beggiatoa* sp., *Streptococcus* sp.), these microorganisms have also been observed in biofilms from studies with drinking water and wastewater from WWTP, they predominate in the biosolid, even under limited substrate conditions (COD less than 40 mg/L) [3,22,23]. Dissolved oxygen concentrations less than 2 mg/L (such as those obtained in the lower zone of the reactor) are related to the growth of filamentous bacteria [25]. The low number of filamentous bacteria allows the formation of small and weak flocs that

Table 1
Basic water quality of the influent

Parameter	Value
pH	6.7 ± 1.20
DO, mg/L	3.0 ± 0.85
COD, mg/L	468.5 ± 26.16
BOD_5, mg/L	224.4 ± 37.91
TS, mg/L	715.0 ± 16.72
TDS, mg/L	611.0 ± 10.85
TSS, mg/L	104.0 ± 20.13

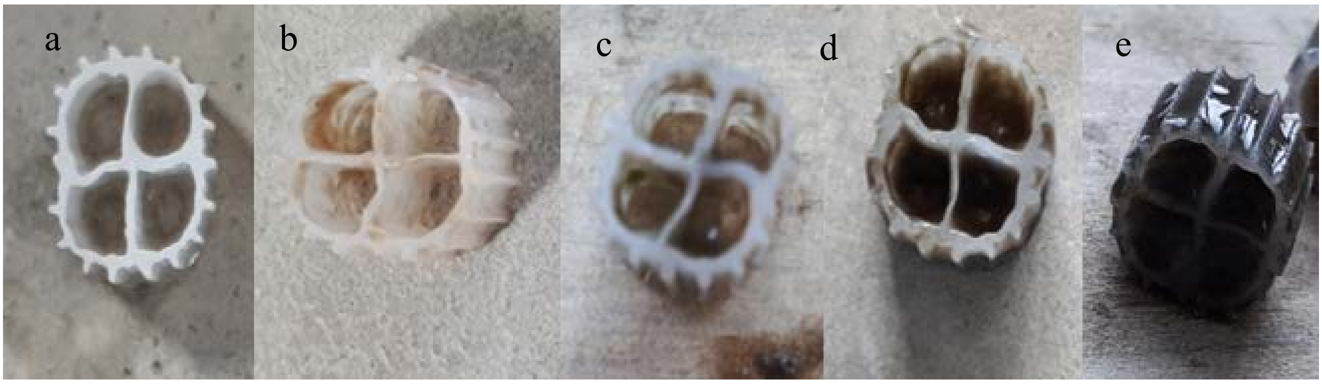

Fig. 2. Biofilm formation in the sequential oxic-anoxic bed reactor (SOABR). (a) day 1, (b) day 5, (c) day 10, (d) day 25, and (e) day 170.

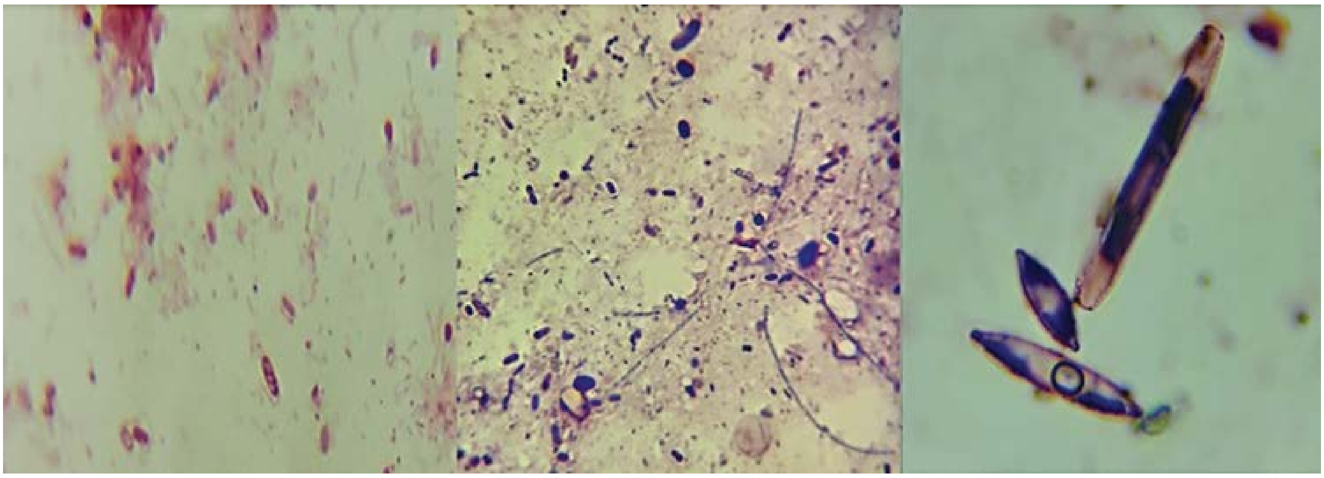

Fig. 3. Images of the microorganisms of the biofilms by using an optical microscope (1000x).

do not sediment and a cloudy effluent was observed. In the upper areas in a study of Xu et al. [24], bacteria such as bacillus and coccus were predominant, in addition to proteobacteria, these last bacteria have been found abundantly (>60%), in environments with different concentrations of dissolved oxygen (0.5–3.5 mg/L). The microorganism communities in biofilms and flocs are responsible mainly for the removal of carbon and nutrients from wastewater [26].

3.3. Scanning electron microscopy

The scanning electron microscopy analysis showed the presence of a microalgae in the SOABR, identified as Chrysophyta. This type of microalgae in effluent treatment is interesting, because the aerobic bacteria degrade the organic matter, and the microalgae assimilate the degradation products and inorganic compounds. There is a favourable microalgae-bacteria interaction, the microalgae in the wastewater treatment process are characterized by supporting high concentrations of nutrients, collaborate with bacterial oxidation and could resist environmental variations [27].

Fig. 4 shows an image of the Chrysophyta, where an elongated valve is observed and a little contracted in the central part, with a series of areoles on the shore, the valve is asymmetric. The white zones on the micrograph are characteristic of calcium.

The growth of diatoms (microalgae) on the plastic matrix helped on the partial elimination of nutrients from the system, in addition, the presence of this type of microorganisms is favourable because they can group together and form filamentous structures.

3.4. Optimal HRT of SOABR-FICCO at start-up

As can be seen in Fig. 2, the biofilm reached optimal development after 25 d, which allowed preoperative testing of the biological reactor at three HRTs. In order to determine the optimal HRT, it was decided to start operating with a wastewater flow rate of 20 mL/min (47.0 h HRT) and then gradually decrease the flow rate to 15 mL/min (31.33 h HRT) for the second run and finally to 10 mL/min (23.5 h HRT), in order to determine the BOD_5, COD, TN and TP removal capacities in the SOABR-FICCO, the results of these parameters are shown in Table 2.

It can be observed that for a HRT of 31.33 h the highest removal percentages of BOD_5, COD and TN (98.5%, 98.79% and 96.77% respectively) were found, while the highest percentage of TP removal was achieved with a HRT of 23.5 (97.23%). This served to define that the most adequate flow

Table 2
BOD_5, COD, TN and TP removal efficiencies in the SOABR-FICCO at different HRTs

	Influent content	Removal % at 23.5 h	Influent content	Removal % at 31.33 h	Influent content	Removal % at 47.0 h
Parameter	mg/L	% Removal	mg/L	% Removal	mg/L	% Removal
BOD_5	162.63	89.3	187.5	98.50	191.96	57.73
COD	422.93	95.96	539.60	98.79	538.55	60.00
TN	42.28	89.12	67.12	96.77	127.67	90.48
TP	2.91	97.23	3.55	81.54	3.15	63.18

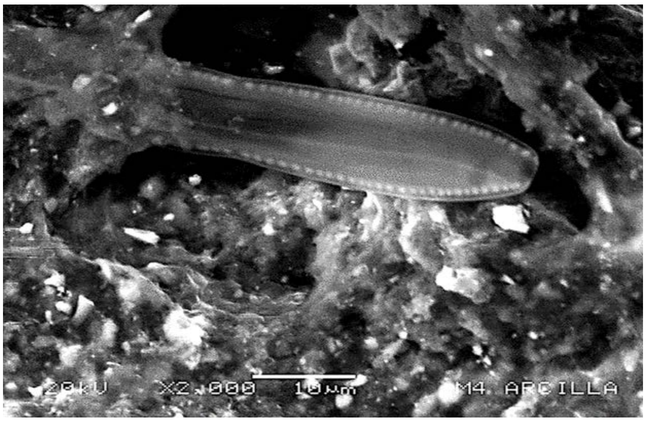

Fig. 4. Crysophyta present in the SOABR.

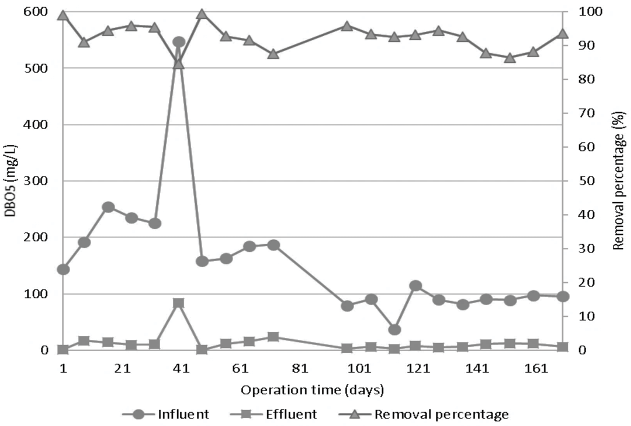

Fig. 5. BOD_5 at the inlet and outlet of the fixed biomass system.

rate to operate the reactor (15 mL/min (HRT of 31.33 h)), the reactor was operated continuously for 170 d to observe its behaviour.

3.5. Reduction of organic and inorganic pollutants

Laboratory measurements were carried out to evaluate the efficiency of the hybrid system to eliminate the organic and inorganic matter, through periodic analysis of the parameters: BOD_5 and COD. According to the BOD_5 corresponding to each day (170) of operation of the bioreactor and considering the effective volume (60%) as empty space once the Kaldnes K1 was contained in the SOABR, it was established that the organic loading rate (OLR) was in the range from 0.077 to 1.13 kg/(m^3 d).

Fig. 5 shows the concentration behaviour and removal percentage of BOD_5 as a function of time, it decreases as the influent passes through each of the stages. The effluent shows better characteristics than that reported by Javid et al. [28] who used a moving bed biofilm reactor for 1 y with different HRTs; the removal of BOD_5 was 88%. Similar efficiencies were reported by Ødegaard et al. [15], with removal percentages between 85 and 95%, and by Mungray and Patel [29] with 93% in fixed biomass processes (up flow anaerobic reactor current combined with an activated sludge reactor). The results obtained in this work were lower than the maximum permissible limits in most weeks of operation; only the week 1, it was slightly above the EPA's maximum allowable limit of 30.0 mg/L [30], which was attributed to the higher concentration of organic matter in the fed solution (547.9 mg/L of BOD_5), this behaviour indicates that there is a tendency to decrease the efficiency with higher organic load in the influent. In this study the FICCO reactor acted as a polishing step in the removal processes of BOD_5 and COD, as well as for the partial removal of nutrients, provided that the HRT of the hybrid biofilm system was longer than 1.5 d.

The COD (Fig. 6) was removed between 85.8% and 97.3% during the 170 d of operation. The removal efficiencies were higher than those reported by Yang et al. [31] and similar to Aygun et al. [32], who also used a fixed biomass system. The concentrations observed in the effluent on days 40 and 72 were 103.6 and 102.1 mg/L respectively, corresponding to removal efficiencies of 85.8% and 81.9% respectively. It is important to note that sudden changes in the influent concentration affect the efficiency of COD removal.

The competition for the organic carbon sources between denitrifiers and phosphorus accumulating organisms (PAOs) induces a lower nitrogen and phosphorus removal from wastewater [33]. Ni et al. [34] reported that the elimination of TN is low when the concentration of organic matter is high (COD of 308 mg/L), therefore, at low concentration of organic matter could lead to a good removal of TN. In this work, low removals from 24.90% to 77.46% of TN were obtained because the COD concentration ranged between 422.93 and 730.9 mg/L in the first 10 determinations. For the last tests carried out, the concentrations of COD were reduced (between 84.71 and 232.96 mg/L)

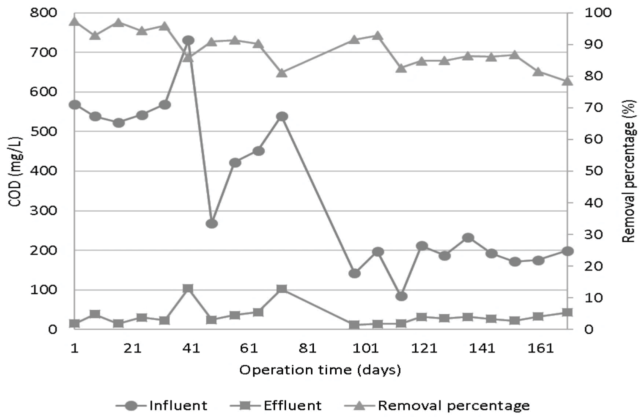

Fig. 6. Total COD in the inlet and outlet of the fixed biomass.

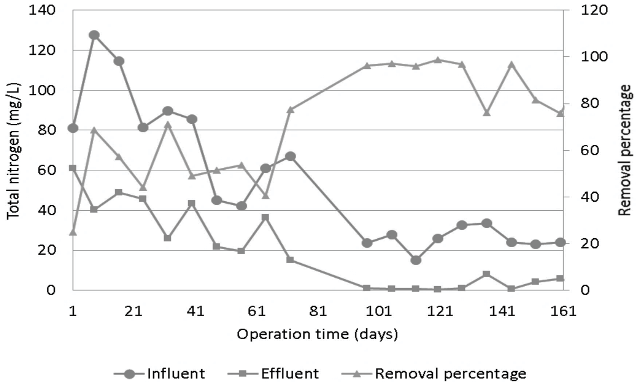

Fig. 7. Total nitrogen in the inlet and outlet of the fixed biomass.

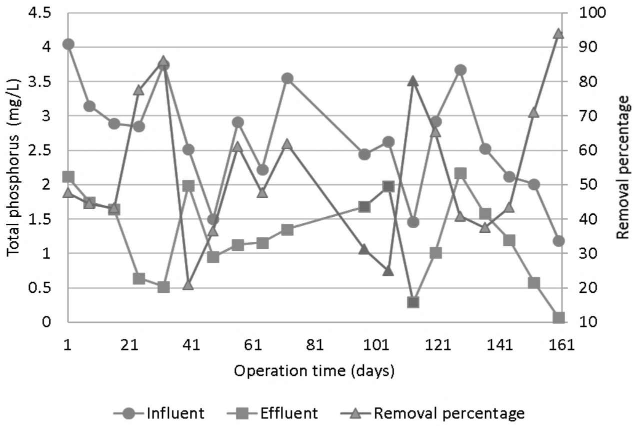

Fig. 8. Total phosphorus at the inlet and outlet of the fixed biomass.

then the TN removal percentage increased from 81.48% to 92.86% (Fig. 7). Another reason for the low removal of TN was alkalinity [35], the pH values obtained in each treatment were close to neutral (6.54–7.50), Peñafiel et al. [36] obtained better results on the removal of ammonia nitrogen (87%) with a system of sand biofilter. In studies on nitrogen removal, the alkalinity/ammonia ratio ranged from 10 to 15, which was favourable for nitrification. On the other hand, the reactors could develop anoxic microzones at the bottom due to their dimensions (with a DO concentration of 0.1 ± 0.03 mg/L), an adequate anoxic zone is important for denitrification and TN removal, some authors have reported that the optimization of the operating conditions in the anoxic zone improves the removal of nutrients [37,38].

The concentration of TN decreased in the oxic and anoxic phases to levels close to zero, which constitutes an indicator of the presence of nitrifying bacteria with good metabolic performance [39,40]. It is inferred that nitrogen removal process occurs due to the formation of anoxic microzones in the biofilm formed in the fixed and mobile contact media [38]. Nitrification occurred on the surface of the biofilm while denitrification developed in the inner layers, due to the DO gradient within the biofilm. The processes to remove nutrients are more complex than those for removing organic matter (BOD, COD); their elimination requires the combination of at least two stages: aerobic and anaerobic in the case of nitrogen [41] and anaerobic and aerobic in the case of phosphorus [40].

The total phosphorus (Fig. 8) behaviour showed highly variability in the effluent with a concentration lower than 2.2 mg/L and removal percentages ranged from 21% to 94%, as shown in Fig. 8. In studies such as that of Peng et al. [42], where investigated the influence of different HRTs under anoxic conditions such as aerobic oxidation/anoxic/aerobic to improve the phosphorus removal, the results showed that the optimization of the operating conditions in the anoxic zone was beneficial for the removal of nutrients [37,38]. Therefore, the size of the anoxic zone should be increased to improve the efficiency of nutrient removal in the treatment of water. Wang et al. [43] suggest the addition of iron sulphate and aluminium salts, since they are highly effective on the removal of phosphorus from wastewater in biofilm reactors, they reported removal efficiencies of 92% and 90% respectively, on the other hand Moawad et al. [44] and Salazar [27] obtained removals of 48%–65% (with concentrations of total phosphorus in the effluent of 1.5 mg/L) and 40%–70%, in batch reactors and treatments with microalgae respectively, furthermore, the removal percentages increased a little as the aeration period increased.

4. Conclusions

The system showed good results on the removal of organic and inorganic contaminants (TN and TP) with a feed rate of 15 mL/min (HRT of 31.33 h) and optimum pH range of 6.5–7.5. The SOABR reactor design and natural aeration allowed the formation of oxic-anoxic microzones that promote the growth of microorganisms of different physiological types. A structurally heterogeneous biofilm developed on the Kaldnes K1 supporting materials, predominantly on the internal surface area with lower colonization than on the external surface. A microscopic examination of the biofilm showed that it is made up of a heterogeneous population of microorganisms, such as bacteria and diatoms, which constantly change depending on the composition of the wastewater and environmental conditions. The FICCO reactor acted as a polishing step on the removal processes of BOD_5 and COD, as well on the partial removal of nutrients, provided that the HRT of the hybrid biofilm system was longer than 1.5 d.

The operation of the treatment system lasted 170 d, and the average removal efficiencies for BOD_5, COD, TP, and TN were 84%–99%, 80%–97%, 21%–94%, and 24%–97% respectively. The biofilms represent an alternative to improve the effluent quality. In this research, it is shown that the nutrients and organic pollutants in the effluent can be reduced to an acceptable level according to international standards by using a SOABR-FICCO configuration.

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Conflict of interest

The authors declare that they have no conflict of interest.

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