Small-Scale Operation of an Integrated Anaerobic Baffled Reactor and Biofilter: Factors Affecting Its Performance

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Abstract: This study aims to evaluate the effect of factors influencing the performance of a small-scale operating wastewater treatment plant (WWTP) integrating anaerobic baffled reactor (ABR) and biofilters with temperature fluctuations in the psychrophilic–mesophilic range. Over nine months of monitoring, the overall removal efficiencies for total chemical oxygen demand (TCOD), soluble chemical oxygen demand, particulate chemical oxygen demand, total suspended solids, ammonia nitrogen (NH_3–N), and phosphorus (P) were 92%, 82%, 98%, 98%, 49%, and 31%, respectively, on average. The ABR's TCOD removal efficiency (57%) was about 20% lower than the simulated efficiency using the Bremen Overseas Research and Development Association (BORDA)'s ABR design model, implying that temperature fluctuation and intermittent wastewater flow are possibly the factors that most affect performance. Although it was lower than the expected efficiency, the global performance of the system is supported by the significant contribution of horizontal and vertical gravel biofilters. The effluent quality complies with the local standard for wastewater discharge, except for the high content of nitrogen and phosphorus concentrations, which can be used for crop irrigation. To improve the WWTP performance, we recommend using a primary settler considering the use of a chemically enhanced solid separation process to avoid overloading organic solids in the ABR operation. **DOI: 10.1061/(ASCE)EE.1943-7870.0002047.**

Practical Applications: This study evaluates the efficiency of a domestic WWTP composed of an ABR and horizontal and vertical flow hybrid gravel filters without vegetation located in a small city in Bolivia where temperature conditions are highly variable (8–24°C). The WWTP treats wastewater from a population of 500 families. The WWTP performance under typical OLR, superficial loading rate, and hydraulic retention time (HRT) showed high removal efficiencies of 92% and 98% for COD and total suspended solids (TSS) respectively, obtaining high-quality effluent suitable for crop irrigation. This configuration is adequate for treating high-strength wastewater at low-moderate temperatures that can be replicated as a decentralized water treatment system in small cities with similar climatic conditions. It is recommended to avoid intermittent flow in ABRs to avoid the washout of organic solids. It is also advisable to complement the configuration with the installation of a primary settler that contemplates an enhanced chemical stage to effectively separate organic and inorganic solids before the ABR. In this way, the treatment capacity of these systems could be increased.

Author keywords: Anaerobic baffled reactor (ABR); Efficiency; Small scale; Moderate temperature; Hybrid gravel biofilter.

Introduction

Anaerobic wastewater treatment is widely accepted among various technological options due to its advantages such as low energy consumption, low sludge production, tolerance to high organic loads, energy generation from produced biogas, and low space requirements (de Lemos Chernicharo 2007). However, despite these advantages, there are certain drawbacks, including a long start-up process in the absence of adapted seed sludge, the need for post-treatment processes, requirements for odor control, unsatisfactory removal of nitrogen, phosphorus, and pathogens (de Lemos Chernicharo 2007), and low performance at moderate to low temperatures, an aspect that still needs to be clarified (Gomec 2010).

An average total chemical oxygen demand (TCOD) removal of 70% is expected in anaerobic treatments at temperatures above 20°C (Gomec 2010). Temperature decreases affect the performance of anaerobic reactors since biological processes are slowed (Nachaiyasit and Stuckey 1997); nevertheless, the development of several configurations has led to significant performance improvements at low temperatures. Some examples include the expanded granular sludge bed reactor, in which granular sludge develops at high up-flow velocities. When provided with a well-adapted, open form of granular sludge, the system allows high treatment levels for

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low-strength wastewater even at temperatures below 10°C (Kato et al. 1994; Rebac et al. 1995; Van Lier et al. 1996). Another important configuration is the staged multiphase anaerobic (SMPA) reactor system, introduced by Lettinga et al. (1997). The reactors arranged in series allow the growth of consortia of suitable anaerobic microorganisms at each stage depending on the available substrate and specific environmental conditions such as pH and partial pressure of H_2. Thus, the SMPA can prevent sludge in different compartments from mixing and may encourage the production of biogas, resulting in higher treatment efficiencies. Moreover, this system can treat industrial and domestic wastewater within a wide temperature range, i.e., from very low (<10°C) to very high (55°C).

An anaerobic baffled reactor (ABR) follows the SMPA concept as it can separate acetogenesis and methanogenesis along the reactor (Wang et al. 2004; Liu et al. 2020). The ABR was first described by Bachmann et al. (1985) as a series of up-flow anaerobic sludge blanket reactors (UASB) confined in several compartments using vertical baffles to direct wastewater through them. Accordingly, sludge bacteria inside the reactor rise and settle with biogas production, resulting in a high solid retention time (SRT) at relatively short hydraulic retention times (HRT). For municipal/domestic wastewater treatment, HRT typically varies from 6 to 48 h (Bodkhe 2009; Feng et al. 2008; Hassan and Dahlan 2013; Nasr et al. 2009). Within this HRT range, SRTs of up to 100 days are achieved (Grobicki and Stuckey 1992). Furthermore, this fluid flow type reduces bacteria washout and enables the ABR to retain biological mass without using any fixed media.

Since the original design of ABR, numerous modifications have been made to enhance the efficiency and reliability of the reactor in treating industrial and domestic wastewater (Hassan and Dahlan 2013; Liu et al. 2010; Zhu et al. 2014). Several studies have focused on the following factors that affect the performance of ABR: number of compartments (Khalekuzzaman et al. 2018), hydrodynamics (Khalekuzzaman et al. 2018; Xu et al. 2014), and organic and hydraulic loading (Yenji et al. 2021; Xi-quan and Zhao-hua 2008), among others. Among these studies, the effect of temperature dominates. Temperature significantly influences anaerobic processes such as ABR. A decrease in temperature causes the slowdown of the degradation rates of volatile organic fatty acids (VFA) and causes the accumulation of soluble microbial metabolic products (SMP) that increases the COD values at the exit of the ABR (Nachaiyasit and Stuckey 1997). Barber and Stuckey (1998) and Zhu et al. (2014) showed that the ABR performs well in treating medium- and high-strength soluble industrial and agricultural wastewater at mesophilic temperatures, with COD removal efficiencies exceeding 95%. Regarding the treatment of domestic or municipal wastewater, which is generally low-strength, COD removal efficiencies above 80% have been reported in the 25–35°C interval (Feng et al. 2008; Nasr et al. 2009). Other studies have been conducted at a wider range of temperatures varying from psychrophilic to mesophilic (Ayaz et al. 2015; Feng et al. 2008; Gomec 2010; Hahn and Figueroa 2015; Nasr et al. 2009; Schalk et al. 2019), reporting variable COD removal efficiencies from 43% to 84%. At low temperatures, the efficiency of ABRs is mainly attributed to the retention of particulate organic material within the ABR (Schalk et al. 2019).

Most studies were carried out at laboratory- or pilot-scale under controlled conditions and do not necessarily reflect the operational reality of large-scale treatment plants. For example, in an evaluation carried out by Yulistyorini et al. (2019) on 89 treatment plants based on ABRs in Indonesia, only 14% showed acceptable performance, with biological oxygen demand (BOD) removal in the range of 25%–98% (mean of 74%), averaging 67 $\mathrm{mg\text{-}BOD_5/L}$ in the effluent, which does not meet Indonesian standards ($< 30\ \mathrm{mg\text{-}BOD_5/L}$) for wastewater discharge. These results were related to deficient infrastructure and lack of maintenance; however, the deficient performance of other examples was attributed to design and operating parameters. In this context, it is important to investigate the performance of full-scale treatment systems under real operating conditions, i.e., wastewater and atmospheric temperatures and dynamic flow and load conditions.

The efficiencies achieved by ABR, especially in areas of moderate to low temperatures, are lower compared to other secondary treatment processes; in addition, they have poor performance in the removal of nitrogen, phosphorus, and pathogens, thus requiring a polishing treatment. Constructed wetlands (CW) integrated with other processes are considered promising complementary treatments due to their simplicity and low energy consumption (Dornelas et al. 2009). Among these, the so-called hybrid CW, which are a combination of horizontal and vertical subsurface flow wetlands, have shown better performance than individual unit systems (Otieno et al. 2017). These systems have been used in combination with ABRs, reaching up to 90%, 89%, and 80% in the removal of COD, total suspended solids (TSS), and TKN, respectively (Ayaz et al. 2015; Singh et al. 2009; Ali et al. 2018; Munavalli et al. 2022). Although the use of plants in wetlands brings advantages, especially in the elimination of organic nitrogen, gravel biofilters, which are essentially CW without vegetation, may be adequate to obtain effluents suitable for use in crop irrigation as they retain nutrients while also having lower maintenance needs. The use of gravel biofilters is uncommon in practice, and the performance of a system integrating ABR and hybrid CW with no vegetation remains poorly understood.

This study focuses on evaluating a WWTP composed of ABR and a no-vegetation hybrid CW comprising a sequence of horizontal and vertical gravel filters (HGF and VGF) to comprehensively understand the factors influencing its performance, such as temperature, HRT, organic loading rate (OLR), and V_{up} on small-scale operation under dynamic conditions. The study area is located in Tolata, Bolivia, with a population of 2,705 inhabitants where the WWTP is operated using a management scheme. The results of this research have important implications for engineers and practitioners to make adjustments to future designs.

Treatment System

Tolata is located in a semiarid area of central Bolivia at 2,720 m above sea level. The annual average air temperature is 16.5°C, with an annual average minimum of 8.8°C and an average maximum of 27°C. The average annual rainfall is 457 mm (SENAMHI 2018). The area's economy is based on agriculture and farming, with maize and alfalfa as the main crops (PDM 2007). The WWTP treats the wastewater received from the sewage system installed in the town of Tolata, which mainly has a domestic origin. It was built and is currently operated by the Aguatuya Foundation.

The WWTP is composed of two parallel treatment trains that combine sequentially an ABR, a HGF, and finally a vertical gravel filter. Both trains are preceded by a pumping station, a rotating screen, and a grease trap. The treated wastewater from both trains is collected in a chamber before entering a chlorination tank and then passes through a sand filter before being deposited in a storage tank for later use in irrigation (AGUATUYA 2015). The whole process is designed to have an HRT of 31 h from influent to effluent. The treatment plant shown in Figs. 1 and 2 were designed to cope with a flow rate of 351 $\mathrm{m^3/d}$ (AGUATUYA 2017).

The pumping station is equipped with a grid chamber (placed before the pumping tank), where large solids are retained. This receives all the wastewater coming from the public sewers, which

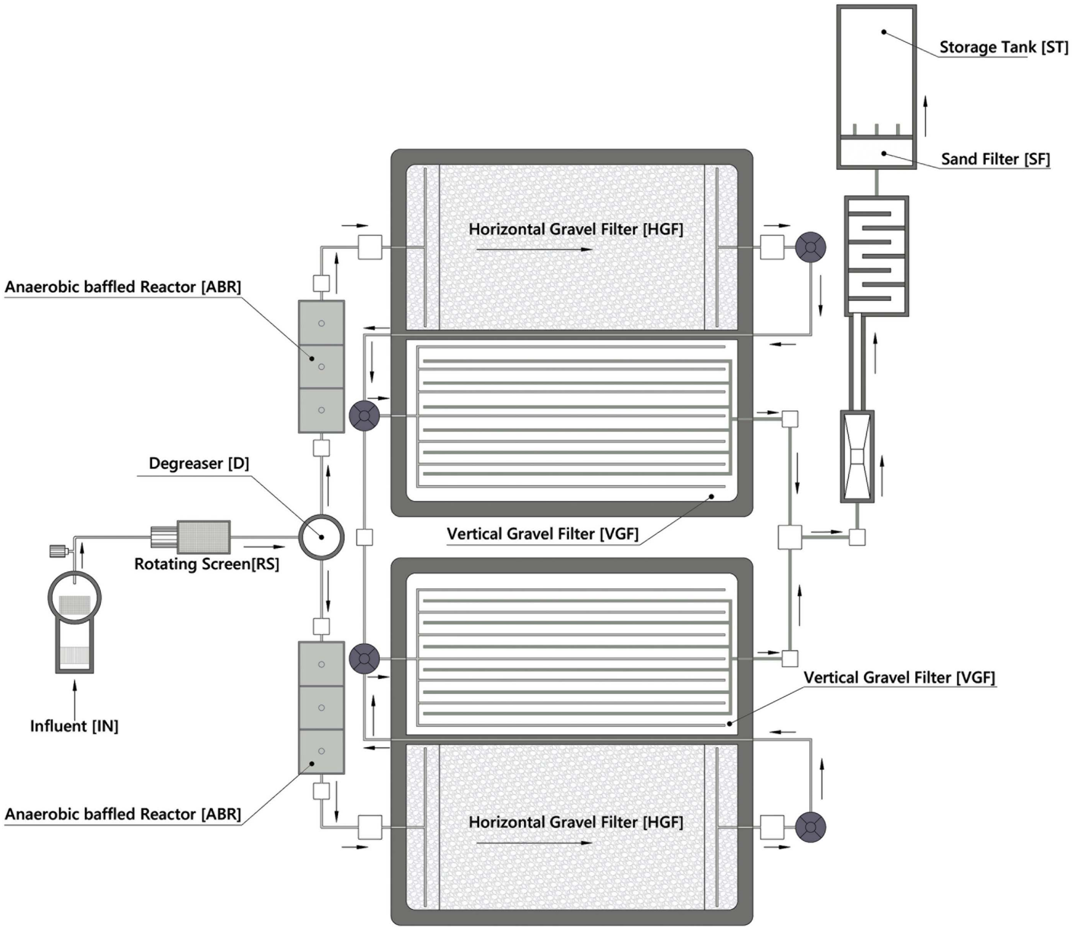


Fig. 1. Plan view of the Tolata wastewater treatment plant.

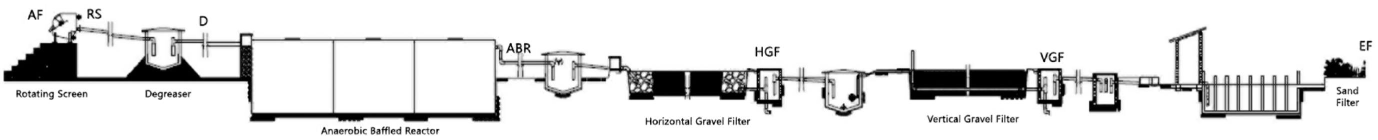


Fig. 2. Sequence of wastewater treatment processes.

then rises it toward the rotating screen (RS). This station also functions as a flow rate equalizer; nonetheless, the flow entering the WWTP is less than the design flow, thus, pumping is intermittent. The RS retains solids >3 mm, which are later dried and transferred to a sanitary landfill. The wastewater then is conducted to the grease trap where fatty material is separated by natural flotation and removed manually. Anaerobic biological treatment is carried out within the ABRs, where organic matter is decomposed into simpler compounds, methane, and carbon dioxide under anoxic conditions. The process generates sludge deposition in the bottom of both ABRs, which is digested and periodically removed through relief valves. The ABRs were designed to have a retention time of 9 h according to recommended design criteria for decentralized wastewater treatment systems (Gutterer et al. 2009). The walls and their baffles are built with fiberglass reinforced polyester (FRP) (Echeverría et al. 2019).

Additional treatment is carried out in the HGF and VGF. At the outlet of each ABR, collecting chambers are arranged to direct the flow to the HGFs, with a total area of approximately 508 m^2 and a depth of 0.8 m. The walls and bottom of the filter are lined with high-density polyethylene geomembrane (Echeverría et al. 2019). At the entrance of each HGF, the solid media is composed of coarse gravel, while the medium-sized gravel (30–32 mm) in the treatment area has a mean porosity between 36% and 40% (Delgadillo et al. 2010). The effluent of the HGF passes through an aeration chamber and is then sprinkled to the VGF through a perforated pipe installed at each entrance. Both VGFs also have an approximate area of 508 m^2 and are packed with medium-sized gravel (Delgadillo et al. 2010).

The sludge accumulated at the bottom of the ABRs is pumped to a sludge drying area of 194.5 m^2 with a depth of 0.15 m. The sludge accumulated at the bottom of the ABRs is pumped to a 194.5 m^2 sludge dryer with a depth of 0.15 m. The sludge removal frequency is about 3–6 months. The sludge that dries in this area is transferred to a sanitary landfill located in the same place. Excess water from the drying area returns to the inlet of the plant (AGUATUYA 2017).

Materials and Methods

In Situ Measurement, Sampling, and Analysis

Nine monitoring campaigns were carried out from October 2018 to July 2019. In every campaign, the flow rate at the WWTP's inlet was measured in triplicate every hour during an 8-h monitoring period using the volumetric method with a stopwatch and a 10-L graduated bucket. The mean of the triplicates was used for further calculation and assessment.

To evaluate the performance of the treatment plant, composite samples (collected every hour during 8-h periods) were taken separately at the inlet and outlet of every treatment process in both treatment sequences. The sampling points were coded as follows: influent to the WWTP (IN), effluent from the RS, effluent from the degreaser (D), effluent from the anaerobic baffled reactor (ABR), effluent from the HGF, effluent from the vertical gravel filter (VGF) and effluent from the sand filter (EF).

On-site pH and temperature (T) measurements were carried out using a multiparameter HANNA HI 98136. Biochemical oxygen demand (BOD_5) was determined by an external laboratory; the TCOD, soluble chemical oxygen demand (SCOD), nitrogen as ammonia (NH_3–N), and soluble phosphorus (P) were measured using a HANNA HI 83099 photometer. Samples for SCOD analysis were initially filtered through a 0.45 μm filter. Alkalinity was determined through acid-base titration; total solids (TS) and total suspended solids (TSS) were analyzed using gravimetric methods as described in the Standard Methods for Examination of Water and Wastewater (APHA/AWWA/WEF 1999). The performance of the WWTP was evaluated based on the characteristics of the wastewater. As for the evaluation of the efficiency of the WWTP, the following parameters were considered: TCOD, SCOD, PCOD, TSS, NH_3–N, and P.

Statistical Data Analysis and Efficiency Simulation

Data were checked for normality and homogeneity of variance by Anderson–Darling and Levene´s tests, respectively. ANOVA one-way and nonparametric Kruskal–Walli's tests were followed by Games–Howell, Tukey, and Mann–Whitney post hoc tests ($p < 0.05$). Mean and median values between IN-RS, RS-D, D-ABR, ABR-HGF, HGF-VGF, and VGF-EF were compared to determine the significance of TCOD, SCOD, TSS, and NH_3–N removal in each treatment process. MINITAB version 19 software was used for the statistical analysis.

In addition to the described monitoring, we applied the guide "Decentralized Wastewater Treatment Systems (DEWATS) and Sanitation in Developing Countries" prepared by the German-based NGO called Bremen Overseas Research and Development Association (BORDA) (Gutterer et al. 2009). This guide provides a semiempirical model to predict the efficiency of an ABR based on collected data from the operation of full-scale installations. It considers the input data of the COD inflow, OLR, HRT, up-flow velocity (V_{up}), and temperature. This model was used for calculating the expected efficiency of Tolata's ABR under the operating conditions measured in this study to verify its influence.

Results and Discussion

Performance of WWTP

As shown in Table 1, this small-scale integrated treatment system shows very high overall removal efficiencies for BOD_5 (98%), TCOD (92%), PCOD (98%), TSS (98%), and SCOD (81%). The removal efficiency for NH_3–N and P were 50% and 34%, respectively. In this table, the results of each treatment process from the influent to effluent depict the mean and standard deviation values. For example, the effluent concentrations achieved were: 11 $\text{mg-BOD}_5/\text{L}$, 80 $\text{mg-TCOD}/\text{L}$, 6 $\text{mg-TSS}/\text{L}$, 44 $\text{mg-NH}_3\text{–N}/\text{L}$, and 8.4 $\text{mg-P}/\text{L}$.

The mean influent pH values for the ABR operation were 7.64 ± 0.27. A slight pH decrease was observed at the exit of the ABR; however, pH values were generally stable and not less than 6.5. The alkalinity values at the influent of the ABR were $1,408 \pm 600\ \text{mg}\,\text{CaCO}_3/\text{L}$, decreasing to $833 \pm 514\ \text{mg}\,\text{CaCO}_3/\text{L}$ at the exit of the reactor.

The high removal efficiencies of biodegradable organic matter and particulate and soluble organic matter show that Tolata's WWTP configuration is advantageous with respect to the predominant treatment technologies operating in Bolivia (Imhoff tanks and lagoon processes), which do not always reach acceptable treatment levels (Cossio et al. 2017).

As for the effluent quality, except for the NH_3–N content, all the parameters satisfy the requirements of Bolivian regulations for discharges to water bodies: (80 $\text{mg-BOD}_5/\text{L}$, 250 $\text{mg-COD}/\text{L}$, 60 $\text{mg-TSS}/\text{L}$, and 4 $\text{mg-NH}_3\text{–N}/\text{L}$) (Bolivian Law 2004). Based on these results, the effluent is more suitable for reuse in crop irrigation than for discharge to water bodies.

Both pH and alkalinity values indicate sufficient stability in the treatment process given the wastewater's buffering capacity. A decrease in pH and alkalinity may indicate certain failures in the anaerobic reactor (Bodkhe 2009), while pH values between 6.5 and 8.5 ensure optimal biological activity (Ramalho 2003).

In relation to the removal of suspended solids, there is an evident increase of TCOD, PCOD, and TSS from the influent to the RS and the degreaser. These increments may result from the dragging of solids caused by the intermittent pumping to the RS and the accumulation of suspended and floating organic matter within the degreaser due to lack of maintenance. A clear correlation was observed among high TCOD, PCOD, and TSS values. The PCOD-TSS correlation indicates that the suspended solids are mostly organic, which is a typical characteristic of domestic wastewater (Metcalf and Eddy 2003). A coefficient of determination of 0.99 confirms the strong correlation between TCOD versus PCOD [Fig. 3(a)] and PCOD versus TSS [Fig. 3(b)].

In this particular configuration, the ABR and HGF are the main contributors to the removal of the organic matter and solid concentrations. As shown Fig. 4, 55% of the TCOD and 65% of the TSS is removed in the ABR. At the HGF, 27% of the TCOD and 26% of the TSS were removed. The VGF and sand filter may be considered as polishing units that further improve effluent quality. The combination of all the units makes high treatment efficiency levels possible, except for the removal of ammonia nitrogen, and phosphorus.

The statistical analysis shown in Table 2 confirmed that the removals of TCOD and SCOD were significant at ABR and HGF processes. Also, the removal of TSS was significant at ABR, HGF, and VGF processes. A significant reduction in NH_3–N was noticed only at the VGF stage. (Fig. 5).

Anaerobic reactors combined with biofilters generally show adequate performance in wastewater treatment. For example, Saavedra et al. (2019) reported the performance of a WWTP comprising UASB reactors followed by biofilters located very close to Tolata's WWTP. Under similar climatic conditions, they reported TCOD removals at the UASB between 35 and 50%, affected mainly by solid biomass washout. In the present study, the ABR reached a TCOD removal efficiency between 42% and 71%

Table 1. Wastewater quality at each process and overall removal efficiency of WWTP

			RS			D			ABR			HGF			VGF			EF effluent		Overall removal efficiency
	IN influent		Effluent		Removal efficiency	Effluent		Removal efficiency	Effluent		Removal efficiency	Effluent		Removal efficiency	Effluent		Removal efficiency			
Parameter	Mean	SD	Mean	SD	Percentage	Mean	SD	Percentage	Mean	SD	Percentage	Mean	SD	Percentage	Mean	SD	Percentage	Mean	SD	Percentage
BOD_5 (mg/L)	479	178	648	220	−35	415	123	36	215	56	48	55	23	74	24	9	56	11	9	98
TCOD (mg/L)	942	229	967	196	−3	989	264	−2	426	152	57	171	75	60	99	53	42	80	39	92
SCOD (mg/L)	360	60	365	57	−1	346	29	5	238	52	31	103	54	57	68	56	34	69	44	81
PCOD (mg/L)	582	135	602	146	−3	643	222	−7	188	89	71	68	44	64	31	26	54	11	29	98
TS (mg/L)	2,154	1,287	2,222	977	−3	2,081	926	6	1,816	945	13	1,556	460	14	1,469	335	6	1,513	661	30
TSS (mg/L)	309	71	334	108	−8	373	194	−12	107	50	71	27	44	75	7	3	74	6	4	98
pH	7.64	0.27	7.58	0.29	—	7.52	0.25	—	6.86	0.19	—	7.05	0.19	—	7.14	0.22	—	7.21	0.21	—
Alkalinity (mg/L)	1408	600	1158	398	—	1058	461	—	1210	731	—	1196	705	—	885	518	—	833	514	—
NH_3–N (mg/L)	87.3	15.7	90.2	10.7	−3	84.3	15.3	7	86.1	19.3	−2	72.9	19.6	15	48.7	16.3	33	43.9	16.7	50
P (mg/L)	12.8	2.3	12.5	2.4	2	11.9	2.7	5	11.3	1.6	5	10.5	2.1	7	9.5	2.2	10	8.4	2.8	34

Note: SD stands for standard deviation.

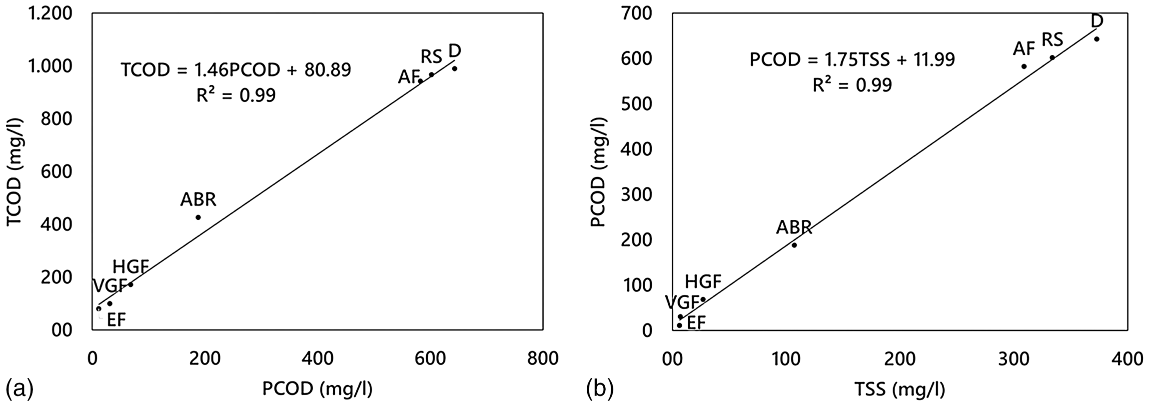


Fig. 3. Correlation between (a) TCOD versus PCOD; and (b) PCOD versus TSS at every stage of the treatment train.

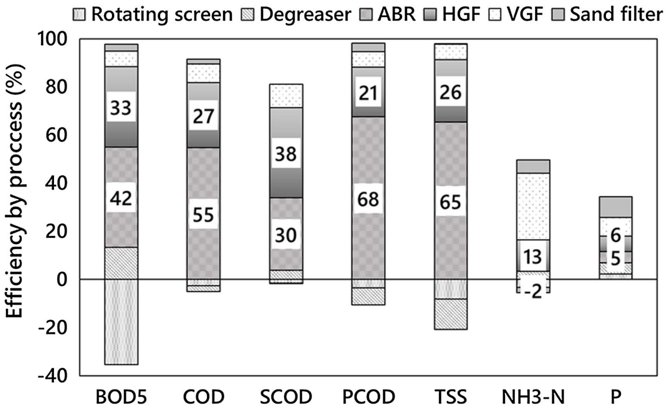


Fig. 4. Contribution by processes to the global efficiency of the Tolata's WWTP.

showing that the ABR is notably advantageous in reducing biomass washout. The results are consistent with those of Manariotis and Grigoropoulos (2006) who reported that the risk of obstruction and sludge bed expansion is minimized in an ABR, thus avoiding biomass purge at the reactor outlet.

Operational Conditions and Treatment Efficiency at the ABR and Biofilters

The operational conditions and efficiency of the ABR process obtained at each sampling campaign are summarized in Table 3. The OLR values of the ABRs analyzed in this investigation were found in the range of 0.43–1.20 kg-COD/m^3 · d. The V$_{up}$ and HRT ranges were 0.43–0.64 m/h and 27–38 h, respectively. The average temperature range in this study was 17.5–23.6°C. The TCOD removal corresponding to these operating conditions was 57% ± 12%.

The treatment efficiency of an ABR depends upon several operational parameters, including inlet concentration, OLR, HRT, number of chambers, and temperature (Reynaud and Buckley 2016), as it is discussed in the following sections. Furthermore, the upflow velocity greatly influences solid retention within the ABR compartments containing sludge, thus influencing the efficiency (Sasse 1998).

The effect of main operational parameters such as organic and hydraulic loading on the performance of ABR was evaluated at laboratory scale. Several studies, treating low to high-strength wastewater (290–1,970 mg-COD/L), reported efficiencies between 52% and 94% under a wide range of OLRs (0.1–3.2 kg-COD/m^3) and HRTs (3–144 h) within a mesophilic temperature range (Bodkhe 2009; Feng et al. 2008, 2015; Koottatep et al. 2004; Nasr et al. 2009). The studies carried out at this level generally do not take into account the effect of dynamic operating conditions and diurnal variations in the amount and concentration of wastewater. As an exception, Abbasi et al. (2017) assessed the effect of fluctuations of OLR and HRT and seasonal climatic conditions on the performance of ABRs. They reported the highest COD removal efficiency as 72% in summer (25–35°C) and the lowest efficiency of 60% in winter (5–15°C), increasing the HRT from summer to winter from 72 to 120 h.

On the performance of ABRs at pilot and field scale (up to 45 m^3/d), under dynamic operating conditions with natural flow fluctuation, Bugey et al. (2011), Sibooli (2013), Reynaud (2015), and Yenji et al. (2021) reported COD removal efficiencies in a range of 22%–90% for an OLR between 0.19 and 8 kg-COD/m^{3}d and HRT between 18 and 55 h. Particularly, Yenji et al. (2021) reported a field-scale study for a wide range of OLR variation (0.03–8 kg-COD/m^3 · d) corresponding to concentrations between 381 and 2,045 mg-COD/L. The efficiencies ranged from 60% to 90%, further demonstrating that ABRs have a high capacity to withstand shock loads. Additionally, they found that the removal of COD and TSS increases with the strength of the wastewater. All these reports correspond to a mesophilic temperature range.

Our results were compared with those of Ayaz et al (2015), Hahn and Figueroa (2015), Schalk et al. (2019), Saif et al. (2021), and Pfluger et al. (2018) who reported the efficiency of pilot-scale or full-scale ABR under moderate-low temperatures and dynamic operating conditions. These references were included in Table 3.

Effect of Organic Loading, Hydraulic Retention Time, and Up-Flow Velocity on ABRs Efficiency

The OLR of this research lies within the range reported for other full- and pilot-scale ABR (See Table 3) and below the maximum design COD load, 3.0 kg-COD/m^3 · d, recommended by Gutterer et al. (2009). Concerning pilot-scale studies (ABR volumes between 0.7 and 9.8 m^3) at low-moderate temperatures, Ayaz et al. (2015) reported a COD removal efficiency of 50% under similar load conditions of 0.3–0.7 kg-COD/m^3 · d at a temperature of 12°C. Hahn and Figueroa (2015) showed a lower efficiency of 43% in a temperature range of 12–23°C for an OLR of 1.3 kg-COD/m^3 · d; Schalk et al. (2019) reported a COD removal

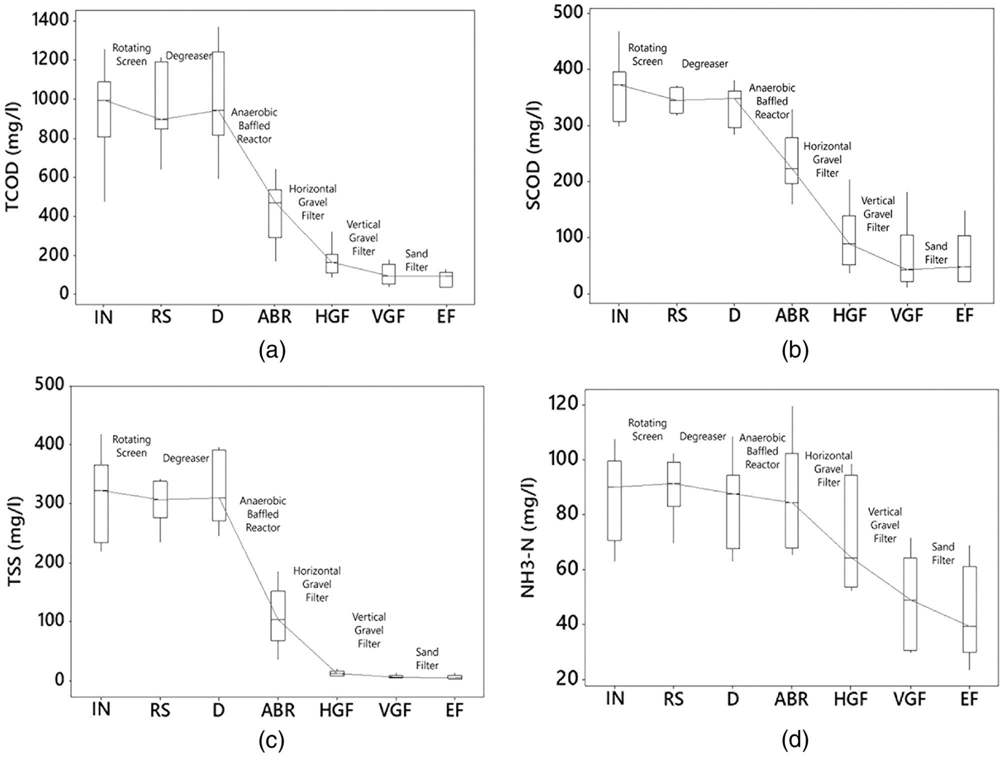
Table 2. Statistical tests employed for the analysis of reduction of TCOD, SCOD, TSS, and NH_3–N in each process treatment

Parameter	Normality Anderson-Darling's test[a]	Homogeneity of variance Levene's test[b]	One-way-test				
			ANOVA Kruskal-Wallis	Mann–Whitney	Significance	Games–Howell Tukey	Significance
TCOD, mg/L	True	False	S (1)	—	—	(1) IN-RS	NS
						RS-D	NS
						D-ABR	S
						ABR-HGF	S
						HGF-VGF	NS
						VGF-EF	NS
SCOD, mg/L	False	True	S (2)	IN-RS	NS	—	—
				RS-D	NS		
				D-ABR	S		
				ABR-HGF	S		
				HGF-VGF	NS		
				VGF-EF	NS		
TSS, mg/L	False	False	S (2)	IN-RS	NS	—	—
				RS-D	NS		
				D-ABR	S		
				ABR-HGF	S		
				HGF-VGF	S		
				VGF-EF	NS		
NH_3–N, mg/L	True	True	S (2)	—	—	(2) IN-RS	NS
						RS-D	NS
						D-ABR	NS
						ABR-HGF	NS
						HGF-VGF	S
						VGF-EF	NS

Note: Post hoc tests: One-way ANOVA was followed by multiple comparisons of means (p values adjusted according to Bonferroni) post hoc ($p < 0.05$); One-way ANOVA (for unequal variances) was followed by Games–Howell's post hoc test ($p < 0.05$); and Nonparametric Kruskal–Walli's test was followed by Mann–Whitney's test of multiple comparisons (for independent samples) post hoc test ($p < 0.05$). NS not significant, and S significant for all one-way test p values <0.05.

[a]True = all the groups (IN, RS, D, ABR, HGF, VGF, EF) have normal distributions.

[b]True = equal variances.



(a) (b)

(c) (d)

Fig. 5. (a) TCOD concentration; (b) SCOD concentration; (c) TSS concentration; and (d) NH_3–N concentration at the end of each component of the treatment train.

Table 3. Operational conditions and efficiency of the ABR process

Monitoring	TCOD in (mg/L)	Flow (m^3/h)	Up-flow velocity (m/h)	HRT (h)	OLR (kg-COD/m^3d)	Temperature (°C)	TCOD efficiency (%)
1st	590	3.9	0.53	33.2	0.43	22	71.2
2nd	1,374	3.7	0.49	35.5	0.93	23.6	66
3rd	803	4.7	0.64	27.6	0.7	22.8	69
4th	1,374	4.7	0.64	27.6	1.2	23.4	66
5th	828	3.2	0.43	41	0.48	22.4	59.3
6th	943	4	0.53	32.8	0.69	21.5	54.6
7th	838	3.3	0.44	39.7	0.51	20	42.5
8th	1,111	3.5	0.48	36.8	0.72	19.2	47
9th	1039	4.5	0.61	28.9	0.86	17.8	38.3
Mean	989	3.9	0.53	33.7	0.7	21.4	57.1
Reference range[a]	460–760	0.03–6.3	0.36–1.00	12–30	0.3–3.24	9–34	40–62

[a] From full and pilot scale studies reported by Ayaz et al. (2015), Hahn and Figueroa (2015), Schalk et al. (2019), Pfluger et al. (2018), and Saif et al. (2021).

of 52% under an OLR of 0.43 kg-COD/$m^3 \cdot$ d at 15.4°C. Similarly, Pfluger et al. (2018) showed a COD removal of 49% for an OLR of 0.5 kg-COD/$m^3 \cdot$ d in a temperature range of 14.8 to 20.5°C. All these COD removal efficiency results are comparable to those of our study (57%) under similar ranges of OLR and temperature.

The study of Saif et al. (2021) corresponds to a larger reactor scale (92 m^3) comparable to the scale of our study (65 m^3). These authors report a COD removal efficiency of 40%–47% for an OLR range between 0.125 and 0.28 kg-COD/$m^3 \cdot$ d, treating a domestic wastewater with a COD inlet concentration between 104 and 233 mg-COD/L under a temperature range between 13 and 34°C. This lower efficiency may be related to the low wastewater COD concentrations. In our study, a 57% COD removal efficiency was observed with higher wastewater concentration (989 mg-COD/L), as discussed by Yenji et al. (2021).

The intervals of HRT and V_{up} reported here also satisfy the design limits recommended for ABRs: HRT >8 h and $V_{up} < 1$ m/h (Gutterer et al. 2009). Additionally, our results are similar to the reference range of pilot and full-scale studies at moderate temperatures (12–30 h and 0.36–1.0 m/h). In general, the operating conditions are similar to those of common practice in full-scale ABR.

In Fig. 6 the observed values of TCOD removal lie below the line simulated by the BORDA tool which relates TCOD removal with HRT and V_{up} at a mean ABR effluent temperature of 21.4°C. The observed values in the range of this study (17.5–23.6°C) were lower than those simulated at 21.4°C. Additionally, it is observed that the simulated efficiency reached its maximum value of 80% at an HRT greater than 20 h. This verifies that efficiency is more limited by temperature rather than HRT or V_{up}.

This comparatively low performance might be additionally explained by the strong influence of the hourly temperature variability and the occurrence of hydraulic shocks caused by intermittent pumping, preventing the V_{up} and HRT from being uniform. These factors are described as follows.

Effect of Temperature Variability on ABRs Efficiency

In the study area, atmospheric temperatures were highly variable, ranging from 3 to 31°C during the monitoring period of October 2018 to July 2019 based on stations operated by

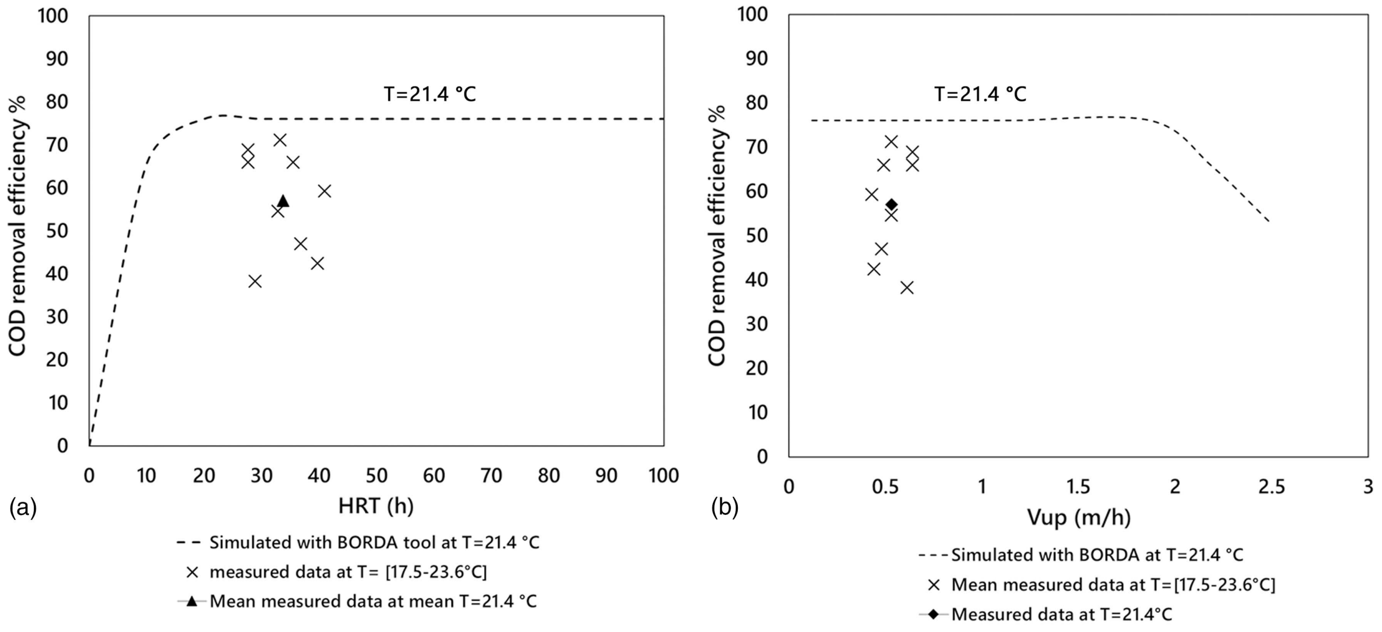


Fig. 6. (a) Simulated and measured COD removal versus hydraulic retention time; and (b) simulated and measured COD removal versus up-flow velocity, V_{up}.

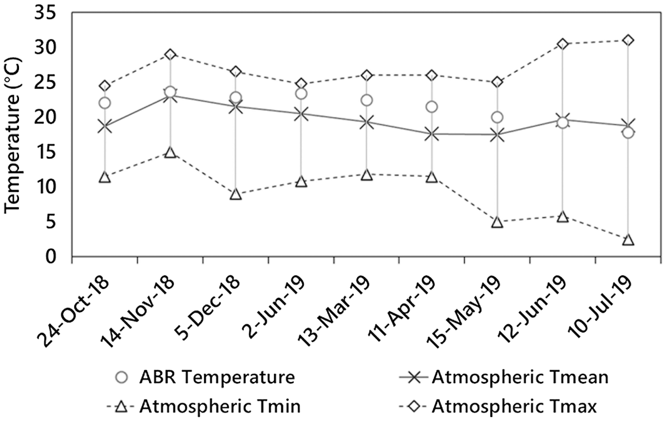


Fig. 7. Atmospheric and wastewater temperatures during the period of the study.

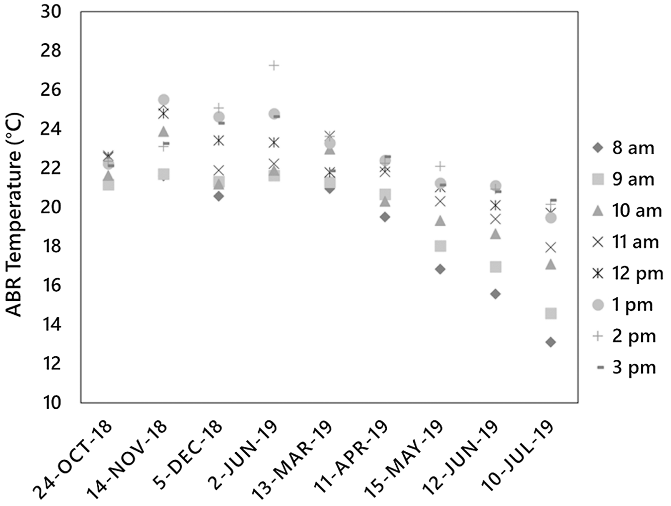


Fig. 8. Hourly variation of temperature at ABR.

SENAMHI (2018). This variability shows the minimum, maximum, and mean atmospheric temperatures, together with the mean wastewater temperature at the ABR (Fig. 7). In addition, hourly variations in wastewater temperature at the ABRs are shown in Fig. 8.

The average wastewater temperature at the ABR does not show large variations (17.5–23.6°C), actually, it fluctuates in a narrow range within the psychrophilic and mesophilic temperatures. However, large variability of temperature at the ABR during the day was found, 11 to 27°C from 8 a.m. to 3 p.m. Nocturnal monitoring would make this temperature range even wider. Under these conditions, it is expected to occur even wider variations of the microbial activities would affect COD removal.

In our study, the clear dependence of efficiency on temperature is considerable (Fig. 9) is noticed. Similar behavior was reported by Saavedra et al. (2019) for a UASB-HGF configuration located in the same geographical zone and under similar climatic conditions.

A graph of efficiency as a function of temperature that confirms this correlation is shown in Fig. 10. The additional dotted line represents the expected efficiency in the same temperature range according to the design criteria of the BORDA guide.

The graphs show similar linear trends in the dependence between efficiency and temperature, as evidenced by the slopes.

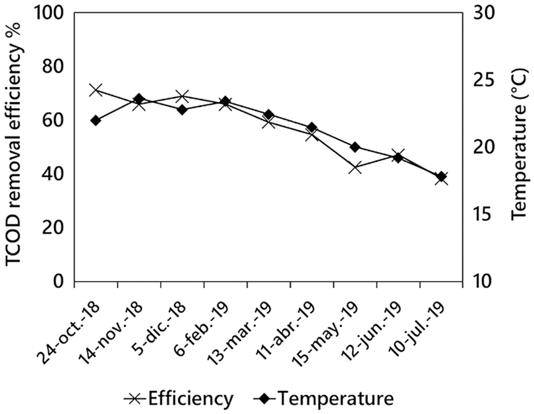


Fig. 9. Relation between TCOD removal and temperature at ABR.

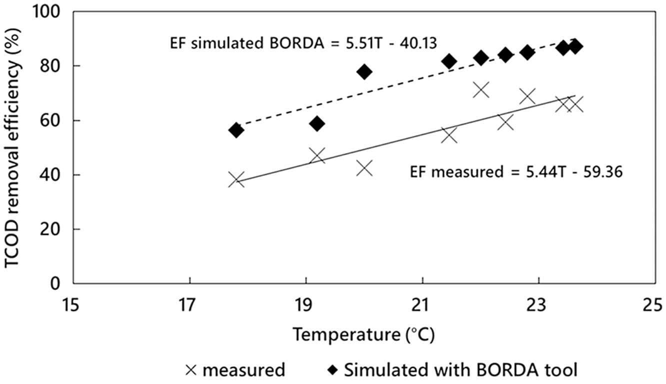


Fig. 10. Effect of temperature on TCOD removal efficiency.

It can be noticed that the measured efficiency is lower than the simulated efficiency. Although this correlation is valid only for this particular WWTP, it provides a useful reference to estimate the efficiency of ABRs under similar operating conditions.

Effect of Flow Pattern on ABRs Efficiency

The flow rates presented in Table 3 represent the average of eight campaigns. In each campaign, the flow measurement was performed hourly for 8 h. In the actual operation of the WWTP, the input flow to the ABR is nonuniform since the wastewater is received in a lift station and then intermittently pumped to the RS and degreaser, from which it is distributed to both parallel ABRs. The average flow received by the lifting station is 1.1 L/s and the pumping flow is 4 to 6 times higher; thus, the ABR receives an intermittent flow of wastewater and experiences hydraulic shocks. Intermittent flow and low temperatures can cause the occurrence of hydraulic dead spaces, thus decreasing the actual HRT as discussed by Haque and Hasan (2018). Moreover, the number of compartments can be related to a decrease in the presence of dead spaces. The ABR of this study has three compartments that are less than the number recommended by Xu et al. (2014) (four or five compartments) to achieve optimal and economic performance.

Additionally, to prevent wastewater flow from being uniform, this pumping regime causes the drag of particulate organic material from the lift station tank to subsequent units, overloading the pretreatment units and, consequently, the ABR. This solids overload can affect ABR performance in terms of COD removal. Some studies of full-scale treatment plants have concluded that an ABR's operational performance, especially in combined collection systems (as presented here), depends on the efficiency of the pretreatment units. Inefficient pretreatment may affect the management of solids in the ABR, requiring a greater effort and frequency of maintenance for desludging (Schalk et al. 2019).

The transfer of the substrate to the microorganisms, uniformity of environmental factors, and effective use of the reactor volume are guaranteed when the flow pattern is uniform (Xu et al. 2014). In this study, uniform flow is not accomplished. This condition, together with the variability of temperature, are possibly the causes of the suboptimal COD removal. Under constant flow conditions, the granular biomass would not suffer disturbances, disintegrations, and washouts, so greater total COD removal is likely.

Operational Parameters and Efficiency of Horizontal and Vertical Gravel Filters

The superficial loading rate (SLR) that HGF and VGF received was in the range of 107–300 g-COD/m^{2}d and 13–52 g-COD/m^{2}d, respectively. An HRT of 86 h for HGF and VGF was registered as is shown in Table 4. Removals of 59%, 79%, and 16% of COD, TSS, and NH_3–N in HGF and 44%, 46%, and 32% of COD, TSS, and NH_3–N, respectively, in VGF corresponding to these operational conditions were reported in this study.

The use of combined horizontal subsurface flow and vertical flow CWs (called hybrid CWs) has proven to be very advantageous in combination with anaerobic processes. Anaerobic treatment prevents biofilters from clogging, whereas horizontal flow wetlands remove organic matter and vertical ones provide nitrification (Ayaz et al. 2011, 2015). The observed efficiency values of this research were slightly lower than those reported by Singh et al. (2009), who evaluated a treatment system configured by ABR and a hybrid CW, a similar configuration of Tolata´s WWTP, with the difference in the hybrid gravel biofilters that are unplanted CWs. In the horizontal subsurface flow wetland, Singh et al. (2009) reported efficiencies of 51%, 69%, and 24% of COD, TSS, and NH_3–N, respectively; the equivalent removal values in vertical flow wetland were 46%, 58%, and 70.9% of COD, TSS, and NH_3–N, respectively. These efficiencies are comparable to our results except for the removal achieved in the vertical flow wetland, which is greater in planted wetlands than in biofilters. Also, removals in the range of 77%–94% COD, 81%–96% TSS, and 74%–99% NH_4^+ have been reported in hybrid CWs by Sayadi et al. (2012). Planted CWs are more efficient at removing pollutants (Dornelas et al. 2009), especially nitrogen, likely since plants regulate biochemical pathways by increasing oxygen supply (Paranychianakis et al. 2016). Since these effluents are used for irrigating crops, it is desirable to conserve nutrients; in this regard, gravel biofilters are a more economical option concerning operation and maintenance as a polishing treatment. Additionally, 72-h HRT is recommended for the operation of hybrid systems for economic and technical reasons (Cui et al. 2006). This difference may indicate that increasing the treatment capacity of these filters may be possible by increasing the flow rate.

Table 4. Operating parameters of the HGF and VGF during the monitoring period

Monitoring	TCOD in (mg/L)	HRT (h)	SLR (g-COD/m^2 d)	TCOD efficiency (%)
			HGF	
1st	169.8	84.8	106.9	43.1
2nd	467.7	90.5	233.2	64.1
3rd	249.3	70.3	175.5	50.5
4th	467.7	70.3	300.2	64.1
5th	337	104.6	121.5	74.7
6th	427.7	83.7	173	63.5
7th	481.7	101.2	127.1	65.2
8th	588.3	94	181.6	45
9th	641.2	73.7	216.6	60.8
Mean	425.6	85.9	181.8	59
			VGF	
1st	96.6	84.8	17.5	51.5
2nd	168	90.5	28.5	43.3
3rd	123.5	70.3	27	50.7
4th	168	70.3	36.7	43.3
5th	85.2	104.6	12.5	56.2
6th	156	83.7	28.6	54.9
7th	167.5	101.2	25.4	20.5
8th	323.3	94	52.9	44.6
9th	251.3	73.7	52.4	29.6
Mean	171.1	85.9	31.3	43.8

Conclusions

This study focused on evaluating the efficiency of Tolata's WWTP, located in the high valley of Cochabamba, which is a semiarid area with large daily temperature fluctuations, where water is a limited and valuable resource for crop irrigation. Thus, evaluating the feasibility of combined ABR-HGF-VGF treatment to achieve acceptable standards for reuse is of particular importance.

The global efficiency results obtained from October 2018 to July 2019 were as follows: 92% of TCOD, 82% of SCOD, 98% of PCOD, 98% of TSS, 49% of NH_3–N, and 31% of P. The effluent concentrations were 11 mg-BOD$_5$/L, 80 mg-TCOD/L, 6 mg-TSS/L, 44 mg-NH_3–N/L, and 8.4 mg-P/L which, except for the nutrient content, comply with parameter thresholds specified in the Bolivian legislation for WWTP discharge. This WWTP showed highly efficient removal of BOD$_5$, COD, and TSS. The ABR and horizontal-vertical gravel filter stages contributed the most to the global efficiency.

The simulated efficiency of the ABR under the studied temperature range and operational conditions (HRT, OLR, and V_{up}) were calculated using the BORDA tool. An efficiency of 57% was observed for a temperature range of 17.5–23.6°C, lower than the simulated 78% efficiency at a mean temperature of 21.4°C for optimal ABR performance, indicating that temperature limits the efficiency the most. Another factor that may affect the performance is the intermittent flow regime due to on-and-off pumping.

In order to improve the performance of the treatment, we recommend the following actions. First, providing a more continuous flow into the system to obtain a constant up-flow velocity within the ABR could improve residence time. Another factor that could contribute to ABR efficiency is the implementation of a primary settler, considering the use of a chemically enhanced solid separation process that could reduce the inflow of inorganic and organic particulate matter. The frequent maintenance of all treatment units is an important factor to reach the optimal performance of all components of the system. Due to the content of nutrients in wastewater, we recommend its application in crop irrigation limiting to tall-stem crops or those that are not consumed unprocessed in order to avoid the implicit microbiological risks.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

Acknowledgments

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