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Performance of Compact Bio-Contact Oxidation Reactors for Municipal Wastewater Treatment Under Different Hydraulic Retention Time

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ABSTRACT

This study employed a laboratory-scale continuous upflow bio-contact oxidation reactor to treat 50 L/day of municipal wastewater in Al Rumaitha City, located north of Al Muthanaa Province in Iraq. The reactor configuration consisted of two anoxic-aerobic reactors nested inside each other, with a 1:3 volume ratio of anoxic to aerobic zones. Both the anoxic and aerobic reactors were loaded with K1 bio-media, filling them to 50% capacity for fixing and preserving the biomass. The reactors were operated in a mode that achieved full nitrification-denitrification without any sludge return, relying solely on internal recycling from the aerobic to the anoxic reactor. After biofilm formation on the carriers, three distinct hydraulic retention times (HRTs) were investigated – ranging from 24 to 12 hours – to evaluate their impact on removing biological nutrients from municipal sewage. In this operational approach, the preferred internal recycle ratio and gas/water ratio for effective nitrogen removal were a complete feed rate recycle of 100% and a ratio of 1:5, respectively. The experiment results highlighted that a 24-hour hydraulic retention time was most suitable for the simultaneous removal of organic carbon (COD) and nutrients. During this period, average removal efficiencies were found to be 93.51% for COD, 94.50% for ammonium (NH_4^+), 60.98% for total nitrogen (TN), and 67.57% for total phosphorus (TP). Furthermore, the aerobic bio-contact oxidation reactors maintained an average dissolved oxygen (DO) concentration of 4.89 mg/L. In contrast, the anoxic bio-contact oxidation reactors exhibited a lower average DO concentration of 0.38 mg/L.

Keywords: traditional systems, eutrophication, space problem, biofilm processes, bio-contact oxidation reactor, hydraulic retention time, nitrification, denitrification.

INTRODUCTION

Historically, wastewater treatment processes aimed to remove particulate material and organic matter. Only in the latter half of this century did eliminating additional elements get significant attention. As time passed, it became necessary to eliminate not only ammonium nitrogen but also the oxidized inorganic forms of this element (nitrite and nitrate), along with phosphorous (Márcia et al., 2011). It was verified that these contaminants (nitrogen and phosphorus) are the primary contributors to water pollution when released into aquatic environments because they reduce oxygen availability, eutrophication, and toxicity, resulting in biodiversity loss and harm to human health (Wang et al., 2005). Researchers found that the microorganisms that remove nitrogen and phosphorus need different environmental conditions, such as the use of anaerobic, anoxic, and aerobic conditions. These led to the construction of new treatment plants, an increase in the number of treatment stages, and the replacement of existing treatment systems, among other things, to maintain the quality of treated water as required by environmental regulations (Márcia et al., 2011).

Due to this, numerous methods (such as the Bardenpho process and others) were created in the 1970s that combined anoxic and aerobic conditions in various tanks. This process presents high nitrogen removal efficiencies, although it requires reactors with a larger total volume (Von Sperling, 2007).

Over time, wastewater treatment plants started to receive more complex and variable polluting loads, especially in large urban areas; as a result, treatment plants had to be adjusted to handle various loads, including water use management and the management and treatment of the liquid residues produced, without requiring a large construction area or even utilizing space that already existed (Rusten et al., 2006). In this context, the development of compact technologies fills the gap left by the absence of traditional systems for treating varied loads and the space issue. Given the above, it is likely that tendencies registered in the last twenty years point to a near future in which, in the great urban centers of the planet, wastewater treatment plants will have an architecture that privileges compact installations, stable operation, and low environmental impact (including odors, noise, and visual effects). Most recently, there has been an escalating fascination with biofilm processes in the context of treating municipal and industrial wastewater, aligning with the aforementioned future objectives. Biofilm reactors are increasingly favored over conventional methods involving suspended biomass, and this preference is supported by various factors. Among these, a crucial factor is the capability to work with high biomass concentrations. These factors enable the reactor to operate under increased loads, a reduced hydraulic retention time (HRT), effective removal of organic compounds, enhanced stability against fluctuations in inlet composition, gradual adaptation to changes in load, temperature, and toxicity, as well as a more efficient separation of solids closer to the reactor's surface. The appeal of biofilm processes is underscored by the more streamlined configuration of these systems and their diminished spatial demands, often serving as pivotal considerations for wastewater treatment facilities (Márcia et al., 2011).

Ødegaard et al. (1994) found that systems using substrate-adherent biomass, such as the bio-contact oxidation reactor, not only do not require conventional sludge recycling in traditional techniques but also allow the biomass to always remain in the reactor, making these systems more specialized for the function they are intended for. An additional aspect to consider is that biofilm-based methods typically exhibit greater capacity for eliminating components from wastewater. This enhanced efficacy largely stems from the diverse array of microbial functional groups present in these environments. Among the prevalent biofilm reactor types employed for the removal of organic substances and key nutrients like nitrogen and phosphorus, you'll find biological trickling filters, aerated submerged fixed-bed biofilm reactors, fluidized-bed reactors, and rotating biological contactors (RBCs). Each of these biofilm reactors has benefits and drawbacks. The RBCs are prone to mechanical failure, and the trickling filter lacks adequate capacity. One problem with fluidized-bed reactors is that they tend to be hydraulically unstable. Another problem with aerated submerged fixed-bed biofilm reactors is that it can be hard to evenly spread the biofilm on the surface of the media (Rusten et al., 1994; Rusten et al., 2006).Therefore, the motivation arose to innovate a bio-contact oxidation technology to overcome these operational problems. This technique was created in Norway in the late eighties, and the first installation started operating in October 1992 in Lardnal, Norway (Rusten et al., 1994; Ødegaard et al., 1994). Thus, this technique gained worldwide notoriety, being extended to other nations (Rusten et al., 2006). In the United States, for example, the first station with this technology was inaugurated in 1995, and having in 2012 more than 36 installations in North America (Qiqi et al., 2012). In France, the first station of this type was inaugurated in 2006, with more than 20 installations until 2012 (Canler et al., 2013). By 2006, approximately 400 full-scale wastewater treatment facilities employing bio-contact oxidation reactor technology were operational across 22 distinct countries (Kermani et al., 2008; Zafarzadeh et al., 2010; Koupaie et al., 2011). By 2014, the count of operational bio-contact oxidation reactor plants had surged to 1200, spread across roughly 50 countries (Biswas et al., 2014). The process bio-contact oxidation technology looked for the best properties of the activated sludge processes and incremented them to the best with bio-filters, leaving out the worst properties of each technique. Many excellent characteristics of bio-contact oxidation technology, especially concerning activated sludge systems, have been listed by several researchers who evaluated the bio-contact oxidation reactor system (Ibrahim et al., 2014; Al-Aboodi et al., 2020; Ødegaard, 2006; Aygun et al., 2008; Dezotti et al., 2011) as follows: (i) the treatment plant requires less space, (ii) the final results are less dependent on the biomass's final separation since the biomass's separation is at least ten times smaller, (iii) the adhered biomass can be used in a more specialized way (there is a higher concentration of relevant organisms) because it does not require sludge return (Igarashi et al., 1999), (iv) they handle high organic loads in a compact way, (v) operating flexibility and ease of installation, (vi) bio-contact oxidation reactors are an excellent option to upgrade existing treatment systems to achieve stricter limits on the effluent pollutant. In the bio-contact oxidation process, a suspended porous polymer is used as a carrier, which moves continuously in the aeration tank. The active mass grows as a biofilm on the bio-media surfaces, contributing to reducing the volume of the decanter and eliminating the need for sludge recycling, as occurs, for example, in activated sludge systems. Also, the concentration of biomass in the bio-contact oxidation process can be increased either by raising the amount of moving media or by using media with a high effective biofilm surface area that enhances resistance to toxicity and consequently improves bio-contact oxidation process performance (Bassin et al., 2011). There are numerous system configurations to promote nitrification and denitrification in bio-contact oxidation reactors. Several researchers have proposed combined anoxic-aerobic systems due to the smaller area required and lower operational costs when conventional biological removal of organic and nitrogen is desired. These systems are promising, as they combine the advantages of the anoxic and aerobic systems: an aerobic zone, whose objective is to conduct nitrification, which is divided into two steps: In the first, ammonium is used by autotrophic ammonia-oxidizing bacteria (AOB) to make nitrite(NO_2^-), and in the second step, nitrite is oxidized to nitrate (NO_3^-) by nitrite-oxidizing bacteria (NOB) (Xu et al., 2014). An anoxic zone uses the nitrate that comes from the aerobic area as an electron acceptor for its reduction to gaseous nitrogen (Sousa et al., 1999). In this way, the nitrogenous portions are removed from the biological system concurrently with organic matter removal. This configuration is interesting because most of the organic matter (COD) present in the influent sewage is removed in an anoxic reactor to promote denitrification, providing a reduction in oxygen consumption and hydraulic retention time for nitrification in the aerobic reactor as there will be greater availability of oxygen for autotrophic microorganisms. Although several studies have been conducted to evaluate the performance of bioreactors in treating domestic wastewater, there needs to be more knowledge regarding the impact of several operational variables on removal performance and bio-carrier activity characteristics using real effluent and under natural conditions. Generally, HRT has significant effects on the efficiency of wastewater treatment systems. However, several other factors, such as seasonal variations, temperature, precipitation, humidity, organic loading, and flow rates, are obvious considerations.

Based on the above, the objective of this study was to evaluate the behavior of lab-scale bio-contact oxidation systems when subjected to variations in the influent composition and verify their operational stability in their ability to remove COD and nitrogen from municipal sewage at different hydraulic retention times, i.e., 24, 16, and 12 hrs. Also, to make sure that this evaluation takes into account the different metabolic steps that happen in biological systems, a system of anoxic-aerobic reactors was set up that favored the degradation of organic matter and nitrification due to the operational conditions imposed on the system. As well as to guarantee the reliability of the data presented here, real effluent from the Al-Rumaitha municipal sewage treatment facility was used to guarantee technological research with direct application, and it is also accompanied by the analytical data involved in these reactors, establishing a relationship between effluent characteristics and microbial diversity. This study also shows a unique design for a system that reduces the size of its footprint by building two anoxic-aerobic reactors nested inside each other, making the system suitable for removing nutrients from domestic wastewater onsite in a small space. In future studies, this study will also help determine and fix the most appropriate HRT for wastewater treatment by building two anoxic-aerobic bio-contact oxidation systems nested inside each other.

MATERIALS AND METHODS

Experimental setup and bio-carriers

The experimental unit consists of laboratory-scale combined anoxic-aerobic bio-contact oxidation reactors with a total work volume of 50 L. The reactors were designed with a 1:3 volume ratio between the anoxic and aerobic zones. In this study, both reactors (aerobic and anoxic) were made of plexiglass. The anoxic reactor (R1) had a working volume of 12.5 L and the following dimensions: 46.5 cm high, 18.5 cm wide, and 18.5 cm long. The aerobic reactor (R2) was 37.5 L; its dimensions were 46.5 cm high, 37 cm wide, and 37 cm long. The system was concluded with a final clarifier 50×50×60 cm. No sludge recycling was implemented in this process. This experiment found that preventing exposure to light was crucial for limiting the growth of algae and other phototropic organisms in this system. The walls were covered with a thick substance to shield the reactor from sunlight. The reactors were assembled in nested form, with real municipal wastewater being fed into an anoxic reactor (R1) to perform denitrification processes, which provided most of the NO_3 nitrate removal, and, in sequence, the aerobic reactor (R2) was constructed to ensure nitrification processes. Figure 1 presents a schematic of the system used, and some important parameters are displayed in Table 1. The influent wastewater for the laboratory plant was withdrawn after the preliminary treatment process of the Al Rumaitha treatment plant, which consisted of roughing, sieving, sandblasting, and defatting. The pretreated wastewater was pumped continuously to the primary sedimentation tank with a capacity of 150 L, where the sedimentation of suspended solids was achieved. This tank is located above reactors to allow wastewater to flow by gravity to the anoxic-aerobic bio contact oxidation reactors without using a pump through an upper-side inlet with a tube, which extends the feed to its base. Both reactors were designed to operate in the up-flow mode since they can handle sizeable influent flow rates and longer working cycles. Also, sampling ports were provided in each reactor for sample collection.

Another critical issue is that these reactors depend on the type of media and the percentage of filling the reactor with media concerning the volume of the reactor. Hence, the selection of a biofilm carrier holds paramount significance as it profoundly influences the system's cost-effectiveness, biofilm formation, and treatment efficacy. Several types of bio-media are used in the bio-contact oxidation reactor process; however, the most commonly used are the supports developed by the company AnoxKaldnes® (Rusten et al., 1998; Salvetti et al., 2006). According to Rusten et al. (2006), the K1 model is the most used, probably due to its format, which allows good hydrodynamics inside the reactor. These supports are fabricated from high-density polyethylene, measuring around 7.2 mm in length and 9.1 mm in diameter. They are cylindrical in shape, white in color, have a specific (internal) surface area of 500 m^2/m^3, and have a density of 0.95 g/cm^3, containing external corrugations and internal divisions (Ødegaard, 2000; Dias, 2011). The biofilm carriers serve as the soul of the system, and the system's performance will fluctuate based on its filling fraction, alongside other parameters. Although Ødegaard et al. (2004) state that the optimal filling range of the reactor is 67%, Wang et al. (2005) opines that, for each

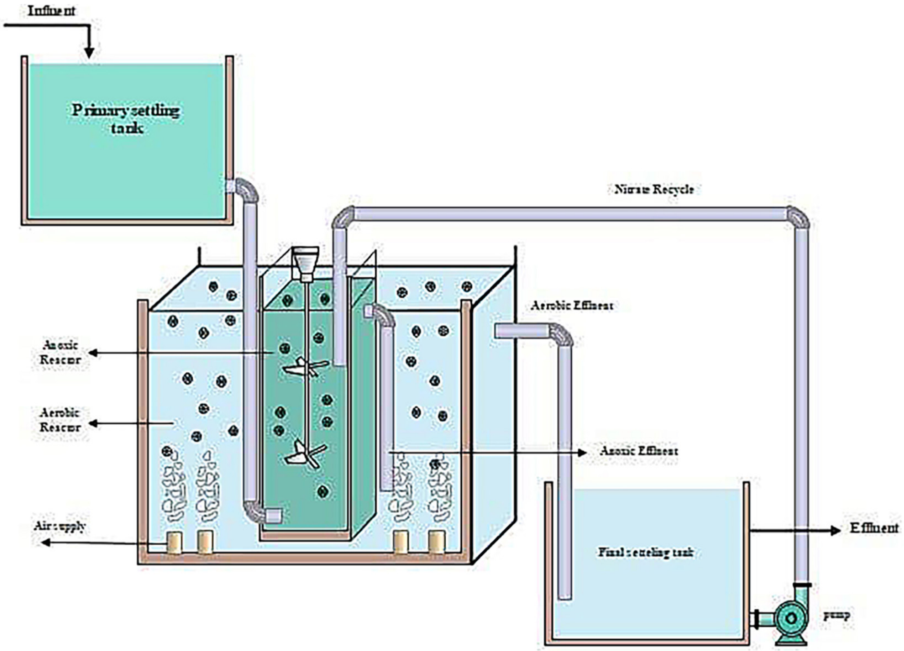

Figure 1. Depicts a schematic of the laboratory-scale bio-contact oxidation reactors

Table 1. Information on the technical details and important parameters of anoxic-aerobic bio contact oxidation

Parameter	Anoxic bio contact oxidation reactor (R1)	Aerobic bio contact oxidation reactor (R2)
Effective volume (m^3)	0.0125	0.0375
Filling ratio with bio-media (%)	50	50
Specific biofilm surface area(m^2/m^3)	250	250
Total biofilm surface area (m^2)	3.125	9.375
Flow rate (L/day)	50	50
Flow direction	Up-flow	Up-flow

Table 2. Kaldnes (K1) bio-media properties

Parameter	Value
Material	high density polyethylene (HDPE)
Form	cylindrical
Dimension (mm)	9.1×7.2
Surface area (m^2/m^3)	500
Filling ratio (%)	30-70
Density (g/cm^3)	0.95

type of system, there is an ideal filling fraction to guarantee the system's proper functioning. The filling fraction will influence the superficial area available for the fixation of suspended biomass and the dynamic movement of parts. Typically, a 30 to 70% filler fraction is used. Values above 70% can cause hydrodynamic problems, such as stagnant regions (Rusten et al., 2006; Aygun et al., 2008; Ødegaard, 2000; Reis, 2007). Due to the above reasons, the fillers used in this study were the K1 media as a bio-carrier in both anoxic and aerobic reactors. The media fill ratio for both reactor types was set at 50%. That is, 50% of the bio-media of the helpful volume of each reactor was inserted, which has been studied numerous times in similar experiences (Salvetti et al., 2006, Germain et al., 2007, Luostarinen et al., 2006, Shore et al., 2012). Kaldnes (K1) media properties are listed in Table 2 for this study.

To complete the uniform distribution of the media inside reactors. The mechanical stirrer was installed in the center of the anoxic reactor. The rotation speed was set to 40 rpm; the stirrer included a 4-blade double with a diameter of 10 cm and blades positioned 15.5 cm and 41 cm below the water's surface. For the aerobic reactor, an aeration system consists of two parallel PVC pipes (1/4 inch in diameter) positioned at a distance of 5 cm from the reactor's base and surrounding the anoxic reactor; these pipes have many small holes spaced at the same distance apart to ensure that the same volume of air is delivered to each section of the reactor. These bottom pipes were connected to an air compressor model TC125506 outside the reactor via vertical lines that ascended above the reactor's liquid level to provide airflow to the R2 reactor. This air compressor had a 100 L/min capacity. In addition, this zone contains a recirculation line from the aerobic reactor to the anoxic reactor at a ratio of 1:1, which fulfills the objective of the denitrification processes. A rotameter controls the airflow, and a manual valve regulates the airflow based on the oxygen measurements in the biological reactor. Aquarium heaters were installed in the anoxic reactor (R1) and aerobic reactor (R2) to maintain the temperatures in the bio contact oxidation reactor at 25–30 °C. During the spring, heating was optional most of the time.

Characteristics of influent wastewater

This work proposes to evaluate the anoxic-aerobic bio-contact oxidation reactor and its capacity to guarantee stability in the face of variations in influent composition. Thus, the raw wastewater characterization is of fundamental importance for understanding the proposed treatment; furthermore, to guarantee the data's reliability, real effluent from municipal wastewater treatment with various concentrations of pollutants was used as the influent. Few works operated in a bio-contact oxidation reactor fed with real effluent for extended periods. Actual sewage was used because it is easier to biodegrade than synthetic wastewater and contains a diverse microbial community. The main effluent quality parameters adopted were: chemical oxygen demand, pH, ammonium, total nitrogen, and total phosphorus. During the entire period of operation of the biological system, sewage characterizations were carried out regularly since its composition can vary over time. Table 3 shows the characteristics of the main contaminants in municipal wastewater.

This trial lasted for 24 weeks (five months). The daily monitoring of the main field parameters, pH, DO, and temperature, was carried out to provide

Table 3. Characteristics of the feed wastewater entering the bio contact oxidation system

Parameter	Unit	Range
COD	mg·L^{-1}	295–500
NH_4^+-N	mg·L^{-1}	29–45
TN	mg·L^{-1}	40–60
TP	mg·L^{-1}	5–7

Table 4. Values of pH, dissolved oxygen, and temperature of the influent, anoxic reactor, and aerobic reactor

Parameter	Influent	Anoxic reactor	Aerobic reactor
pH	7.55–8.15	7.64	7.58
Dissolved oxygen (mg/L)	0.17–0.22	0.38	4.89
Temperature (°C)	25–30	25–30	25–30

the best conditions for the biological process and the growth of particular microorganisms that favor nitrification in the system. The values of these parameters are shown in Table 4 for each sample point: influent, aerobic zone, and anoxic zone.

Inoculum and operation of reactors

An experimental unit on a lab scale was installed and operated in an open environment at the Al Rumaitha plant, a municipal wastewater treatment facility located in Al Rumaitha City, north of Al Muthanaa Province in Iraq. This laboratory-scale plant was used for treating real sewage from the preliminary treatment stage of the Al Rumaitha treatment facility under real process conditions, which experienced daily variations in influent contaminant concentrations and environmental conditions. The acclimatization of K1 used as bio-carriers in reactors is one of the crucial steps in providing suitably active biomass growth on the bio-carriers so that this biomass can function appropriately in the sewage treatment process. On this basis, the anoxic-aerobic bioreactors were inoculated with activated sludge to acclimatize and promote the rapid growth of bacteria inside the bioreactors. The inoculum (seeding of microorganisms) was taken from the same Al Rumaitha municipal sewage treatment facility. Inoculation's three-day seed preparation phase began with collecting the seeds, removing any inorganic material through a small sieve, and three days of aeration at room temperature. On the fourth day, the aeration was interrupted, and the seeding sludge was mixed with the municipal sewage in a ratio of 0.67%. The anoxic reactors were inoculated with approximately 4.25 L of mixed liquid (34% of the working volume). The aerobic reactor had approximately 12.75 L of aerobic sludge (34% of the work volume) from the same liquid. The start-up phase was carried out simultaneously in the reactors after inoculation. This phase was divided into two operating conditions, condition one; the reactors were operated in batch mode with a fill period equal to 4 h and 14 h aeration with a gas: water ratio equal to 10:1 in the aerobic reactor (R2) and mixing in the anoxic reactor (R1), 4-h settling time, and two hours for 100% duration of discharge in this work. In this work, biofilm growth on media was observed after four weeks. At the beginning of the fifth week of operation, condition two was performed; the bio-contact oxidation reactor in an anoxic-aerobic configuration was operated continuously with an influent flow of 50 L/day, a total HRT of 24 h (anoxic HRT of 6 hrs. and aerobic HRT of 18 h), and K1 media at a filling fraction of 50%, with NO_3 recycling from the aerobic reactor to the anoxic reactor at a ratio of 1:1 and a ratio of gas to water equal to 5:1, getting ready for the startup. The sixth week of operation was characterized by the investigation into the impact of hydraulic retention time on the biological nutrient removal from municipal wastewater by operating the reactors under three different hydraulic retention times ranging from 24 to 12 h (24 h, 16, and 12 h) by changing the value of this parameter every specified period. The HRT alteration occurred through changes in the inlet flow to the system (Table 5). The recycling rate was 100% for all analyzed hydraulic retention times. Aeration was maintained at a constant gas/water ratio equal to 5:1, controlled by a rotameter, to provide a dissolved oxygen concentration of approximately 4.89 mg/L so that the absence of dissolved oxygen does not limit nitrification; this value can be considered an indication of an optimal medium for effective elimination of COD and an effective nitrification process considering that, in the biofilm process, the nitrification rate shows a first-order dependence on the dissolved oxygen concentration (Al-Rekabi, 2015). According to Metcalf and Eddy (2016), the DO range adopted to ensure nitrification and minimize the volume of support medium is 4.0 to 6.0 mg/L. While Ødegaard (1994) recommended maintaining a DO concentration between 2 and 5

Table 5. Hydraulic retention time of the system as a function of the influent flow variation

Flow rate (L/day)	Working volume of bio-contact oxidation reactor (liter)	Total HRT (hours)	HRT anoxic reactor (hours)	HRT aerobic reactor (hours)
50	50	24	6	18
75	50	16	4	12
100	50	12	3	9

mg/l without compromising the efficiency of the system, whereas Rusten et al. (1998) recommended a DO concentration between 2.5 to 3.0 mg/l, stating that from these values, the nitrification process is initiated. For this study, the average values of temperature and pH showed stable values with no significant variation over the monitored period. The results of the monitoring of the parameters mentioned above indicated that values considered optimal were maintained in both anoxic and aerobic bio-contact oxidation reactors: average pH values were 7.64 and 7.58, and the temperature was 29 and 30°C, respectively, and dissolved oxygen values for nitrification >2 mg/L and denitrification <0.5 mg/L, whereas the average mixed liquor suspended solids concentration (MLSS Total) in aerobic and anoxic reactors, respectively, was 2421 mg/L and 3119 mg/L.

Sampling and analysis

Samples from the reactor's intake and effluent were collected to evaluate the performance of the lab-scale bio contact oxidation reactors. Each reactor's pH, DO, and temperature (°C) were tested every workday before a sample was taken. A WTW Multiparameter 340i was used for testing DO and pH. DO levels were monitored daily in two reactors and kept above 2.0 mg/L in aerobic bio-contact oxidation reactors to ensure that the bio-contact oxidation reactor was fully functioning for nitrification. and less than 0.5 mg/L in anoxic bio-contact oxidation reactors. The study's analyses of the chemical variables included COD, ammonium, total nitrogen, and total phosphor, which were conducted at the Al Rumaitha wastewater treatment facility's Environmental Laboratory. They were examined using standard procedures described in (State Environmental Protection Administration, 2002). The adhering biomass elements' total suspended solids (TSS) concentration was evaluated using the following steps: Ten bio-media were immersed in a vial of deionized water in an ultrasonic bath for 45 minutes to remove any adherent biomass. The bio-media was then rinsed with deionized water; after that, the solution was filtered via (0.45 μm). The retained solid residue on the filter paper was desiccated in an oven at 105°C for an hour and then weighed. Due to the varying sizes of the bio-media, the calculated TSS concentration was performed across the entire 1 m^3 of reactor surface area. This value referred to the total of the ten media's measured surfaces (Andreottola et al., 2000a; Andreottola et al., 2000b; Helness, 2007).

RESULTS AND DISCUSSION

In this work, experimental units were designed and built to test the use of a fully nitrification/denitrification process using a lab-scaled up-flow bio-contact oxidation reactor in an anoxic-aerobic configuration. They were put together with a 1:3 volume ratio between the anoxic and aerobic zones, and water was recirculated from the aerobic reactor to the anoxic reactor. The system was operated for the removal of organic carbon and nutrients from municipal sewage in Al Rumaitha City, north of Al Muthanaa Province in Iraq, without sludge recycling, an internal recycle ratio of 100%, and 3 different HRTs (24, 16, and 12 h) in order to evaluate the optimum value of HRT for the best nutrients removal. The operational data from the anoxic-aerobic bio-contact oxidation system were provided in Tables 6, 7, and 8 and visualized in Figures 2 through 9.

The hydraulic retention time is an essential operating parameter in wastewater treatment systems, the HRT represents the average time that wastewater remains in the treatment system, and in a bio-contact oxidation reactor, it can have significant effects on the removal of COD (chemical oxygen demand) and nutrients, such as nitrogen and phosphorus. HRT values can widely vary in the literature, where several studies have investigated the effect of different hydraulic retention times on removing chemical oxygen demand in bio contact oxidation reactors. A study by Jahren et al. (2002) evaluated an bio-contact oxidation

Table 6. Reactor performance in COD, NH_4^+-N, TN and TP removal at different HRT in steady-state operation

HRT	COD			NH_4-N			TN			TP		
	Inf. (mg/l)	Eff. (mg/l)	R%	Inf. (mg/l)	Eff. (mg/l)	R%	Inf. (mg/l)	Eff. (mg/l)	R%	Inf. (mg/l)	Eff. (mg/l)	R%
24	455	28	93.85	33	2.31	93.00	54.67	20.41	62.67	6.68	2.1	68.56
24	377	25	93.37	41.3	1.78	95.69	43.34	19.56	54.87	5.76	1.88	67.36
24	389	26	93.32	38.22	1.98	94.82	52.93	18.31	65.41	5.96	1.98	66.78
16	311	27	91.32	29.3	2.64	90.99	47.8	20.2	57.74	5.35	1.45	72.90
16	391	31	92.07	33.1	2.3	93.05	43.67	19	56.49	6.11	1.55	74.63
16	366	28	92.35	42.55	2.88	93.23	52.81	21.55	59.19	6.2	1.68	72.90
12	295	31	89.49	36.45	5.62	84.58	48.31	26.44	45.27	6.4	2.67	58.28
12	376	34	90.96	33.6	5.4	83.93	56.72	29.31	48.33	5.68	3.1	45.42
12	299	32	89.30	40.56	5.35	86.81	52.46	27.78	47.05	5.13	3.45	32.75

Table 7. Average reactor performance in COD, NH_4^+-N, TN, and TP removal at different HRT in steady-state operation

HRT	COD			NH_4-N			TN			TP		
	Av. inf. (mg/l)	Av. eff. (mg/l)	Av. R%	Av. inf. (mg/l)	Av. eff. (mg/l)	Av. R%	Av. inf. (mg/l)	Av. eff. (mg/l)	Av. R%	Av. inf. (mg/l)	Av. eff. (mg/l)	Av. R%
24	407.00	26.33	93.51	37.51	2.02	94.50	50.31	19.43	60.98	6.13	1.99	67.57
16	356.00	28.67	91.91	34.98	2.61	92.42	48.09	20.25	57.81	5.89	1.56	73.48
12	323.33	32.33	89.92	36.87	5.46	85.11	52.50	27.84	46.88	5.74	3.07	45.48

Table 8. Standard deviation of reactor performance in COD, NH_4^+-N, TN, and TP removal at different HRT in steady-state operation

HRT	COD			NH_4-N			TN			TP		
	Inf. S.D. (mg/L)	Eff. S.D. (mg/L)	R. S.D.%	Inf. S.D. (mg/L)	Eff. S.D. (mg/L)	R. S.D. %	Inf. S.D. (mg/L)	Eff. S.D. (mg/L)	R. S.D. %	Inf. S.D. (mg/L)	Eff. S.D. (mg/L)	R. S.D. %
24	42.00	1.53	0.29	4.20	0.27	1.37	6.10	1.06	5.47	0.48	0.11	0.91
16	40.93	2.08	0.53	6.82	0.29	1.25	4.58	1.28	1.35	0.47	0.12	1.00
12	45.65	1.53	0.91	3.50	0.14	1.51	4.21	1.44	1.53	0.64	0.39	12.77

reactor process for its efficiency in removing organic matter from a paper industry effluent. The reactor was operated on a laboratory scale, working in a thermophilic aerobic system (55ºC), with a filling fraction of 58% with Kaldnes K1 supports and a TRH between 13 and 22 hours. They showed a soluble COD removal efficiency of 60–65%. While Gulhane and Kotangale (2014) utilized the bio-contact oxidation reactor system, operating with a 24-hour hydraulic retention time (HRT), to effectively eliminate BOD_5, COD, and total solids from wastewater. Their study revealed a BOD5 removal efficiency of at least 75.48%. Another study by Gonçalves Filho (2019) examined HRT's impact on COD removal in an bio-contact oxidation reactor system to treat dairy effluent. The study found that increasing the HRT resulted in improved COD removal efficiency. The researchers observed that extending the HRT from 13,18 to 27 hours significantly increased the COD removal rate. The author found efficiencies of 99% in COD removal when HRT was 27 hours, 90% at 18 hours, and 84% for 13 hours. An investigation was made by Melin et al. (2005) with bio-contact oxidation reactors with a fill fraction of 70% to treat municipal wastewater. The authors analyzed the effect of different organic loads using different TRH. They achieved average COD removal efficiencies around 45%, 55%, 70%, and 73% for HRT of 0.75, 1, 3, and 4 h, respectively. The results demonstrated that an increased HRT of 4 hours led to higher COD removal efficiency. It is important to note that the specific findings may vary depending on the wastewater characteristics, reactor configuration, operating conditions, and other factors. Still, all research shows that a longer HRT generally promotes COD removal in a bio-contact oxidation system. The extended contact time between the wastewater and the biofilm increases microbial degradation of organic compounds, resulting in higher COD removal rates. The longer HRT allows attached biofilm microorganisms to metabolize and break down the organic pollutants, converting them into simpler, less polluting substances and enhancing COD removal efficiency. For effective nitrogen removal in bio-contact oxidation systems, the effect of hydraulic retention time (HRT) has been extensively studied.

As it is known, the overall process of nitrogen removal encompasses two primary steps: nitrification and denitrification. Nitrification involves the transformation of ammonia (NH_3) into nitrite (NO_2^-) and subsequently into nitrate (NO_3^-), facilitated by distinct groups of microorganisms. Initially, Ammonia Oxidizing Bacteria (AOB) convert ammonia into nitrite, followed by nitrite oxidizing bacteria (NOB) which further oxidize the intermediate product into nitrate. While denitrification takes place under oxygen-deprived conditions, denitrifying bacteria utilize nitrate (NO_3^-) as an electron acceptor, sequentially reducing it to nitrite (NO_2^-), then to nitrous oxide, or "laughing gas" (N_2O), followed by nitric oxide (NO), and ultimately to nitrogen gas (N_2) production (Gray, 1992; Wang et al., 2004). Nitrifying bacteria require sufficient time to oxidize ammonia to nitrate. In the case of a very low HRT, the development of nitrifying bacteria is compromised, especially if the concentration of organic material is high. Under these conditions, only the development of heterotrophic bacteria occurs, which presents growth rates much higher than those given by the autotrophic consortium responsible for nitrification. On the other hand, systems characterized by high HRT values may favor the nitrifying process and improve ammonia removal., since there is enough time for the development of chemolithoautotrophic bacteria active in nitrification (Dezotti et al., 2011). According to Zilli (2013), HRTs impact on nitrogen removal in an bio-contact oxidation reactor system treating industrial wastewater was investigated. The results showed that increasing the HRT from 8 to 12 hours significantly enhanced nitrogen removal efficiency. The longer HRT allowed more time for nitrification and denitrification processes, resulting in higher nitrogen removal rates. They obtained an average efficiency rate of 90% and 92%, respectively, and maximum efficiencies of around 98 and 99%, for ammonia nitrogen. In the anoxic bio-contact oxidation reactor, biological phosphorus removal begins when the phosphorus-accumulating organisms (PAOs) use nitrate as an electron acceptor to assimilate a portion of the biodegradable organic matter. This assimilated material is stored as intracellular granules, serving as a source of growth and energy for subsequent aerobic reactors (Chuang et al.,1998; Tchobanoglous et al., 2003). The longer the HRT, the more time the polyphosphate-accumulating organisms (PAOs) have to take up organic carbon. This way, the anoxic bio-contact oxidation reactor consumption increased to COD, and nitrate was removed. Generally, the dissolved oxygen that was present in the aerobic bio-contact oxidation reactor was utilized by various processes, including those involving heterotrophic organisms (COD removal), autotrophic organisms (nitrification), and the activities of phosphorus-accumulating organisms (PAOs). Simultaneously, organic matter was depleted as a result of the activities of heterotrophic organisms and PAOs. A longer HRT in the aerobic phase allows PAOs to absorb phosphorus from the wastewater, leading to a higher phosphorus removal capacity.

Optimizing the HRT in an anoxic-aerobic bio-contact oxidation reactor for pollutant removal requires a comprehensive understanding of the wastewater characteristics, treatment goals, and system design. The anoxic and aerobic phases of an anoxic-aerobic bio-contact oxidation system each serve specific purposes in pollutant removal. Optimizing the HRT involves finding the right balance between the two phases to ensure efficient removal. The anoxic phase provides denitrification and phosphorus release conditions, while the aerobic phase facilitates organic matter degradation, nitrification, and phosphorus uptake. Adjusting the HRT in each phase allows for sufficient contact time for the respective processes.

Effect of different HRTs on the removal of COD

Figure 2 and Table 6 show the COD concentration at the inlet, concentration at the outlet, and removal efficiency of the anoxic-aerobic bio-contact oxidation system at different HRTs over the operating time, whereas Figure 3 and Tables 7 and 8 show the average COD removal performance of the anoxic-aerobic bio-contact oxidation system. It is possible to observe that the change in TRH had little influence on the removal of COD from the system. Despite the gradual increase in the flow rate by decreasing HRT, the system achieved good levels of COD removal at all the HRTs. It was noted that COD removal at all the HRT conditions was more than 80%. However, the average removal of COD was highest at HRT of 24 h, which was 93.51% (S.D. = 0.29), with a mean final concentration of 26.33 mg/L (S.D.= 1.53). The average COD removal at the 16-h HRT was nearly 91.91% (S.D. = 0.53), and the final concentration was approximately 28.67 mg/L (S.D.= 2.08). When the HRT was 12 h, the average removal was 89.92% (S.D. = 0.91), and the final concentration was around 32.33 mg/L (S.D. = 1.53). The results illustrated that HRT in the range of 24 to 12 did not significantly affect COD removal efficiencies.

Effect of different HRTs on the removal of ammonium (NH_4^+-N)

The bio-contact oxidation reactor's performance in the nitrification step was evaluated by monitoring the NH_4^+ content in the influent and effluent of the system. Figure 4 and Table 6 show the total concentration of ammonium in the influent, effluent, and removal efficiency for the different hydraulic retention times. In contrast, the average performance of the bio-contact oxidation reaction in the removal of ammonium is illustrated in Figure 5 and Tables 7 and 8. It is evident that when HRT decreased, so did the effectiveness of removing ammonium. It ranged from 94.50% (S.D. = 1.37) removal with HRT in 24 hours to 85.11% (S.D. = 1.51) removal with HRT in 12 hours. During the 24-hour TRH, the average ammonium removals were 94.50%, and the final concentration was 2.02 mg/L (S.D.=0.27). With 16-hour HRT, removal was between 90.99% and 93.23%, with final concentrations ranging from 2.30 to 2.88 mg/L. The decrease in HRT appears to have a significant impact on nitrification, unlike COD removal. When the HRT was decreased from 16 h to 12 h, average efficiency decreased, ranging from 92.42 (S.D. = 1.25) to 85.11% (S.D. = 1.51), with approximate concentrations of 5.46 mg/L (S.D.=0.14). The loss of efficiency by the system with the decrease in HRT can be attributed to the effluent's shorter contact time with the microorganisms (nitrifying bacteria), which was insufficient to remove ammonium from the medium and complete the nitrification process.

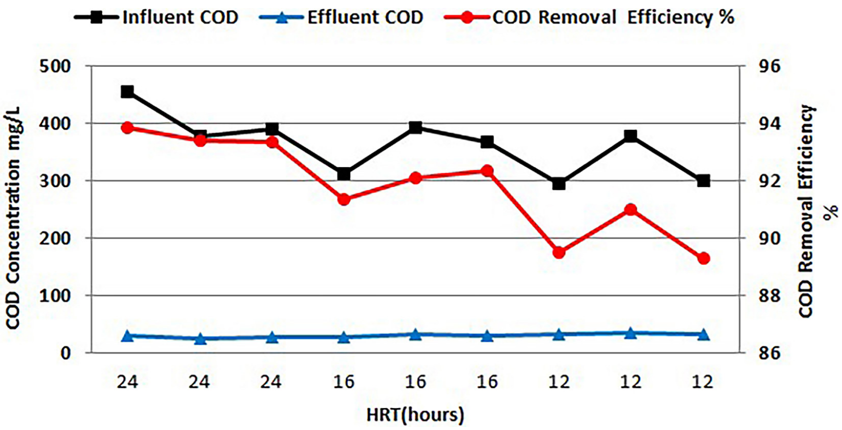

Figure 2. The COD concentration at the inlet, outlet, and removal efficiency at different HRTs

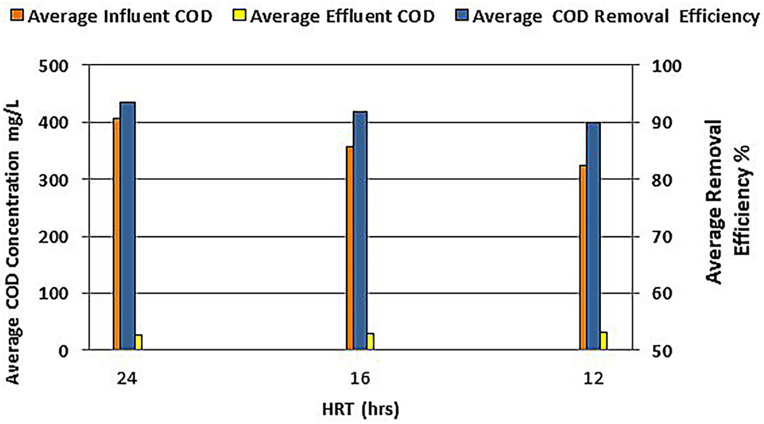

Figure 3. Average concentration of COD and average removal efficiency at different HRT

Nitrification is a crucial step in the biological removal of nitrogen; by biologically oxidizing ammonium and producing the end product, nitrate. The reaction requires the mediation of specific bacteria and takes two sequential steps. In the first step, called nitrification, the ammonium ion (NH_4^+-N) is oxidized to nitrite (NO_2^--N) through the biochemical action of bacteria such as those of the genus Nitrosomonas. In the second step, called nitration, the oxidation of nitrite (NO_2^--N) to nitrate (NO_3^--N) is mediated by the bacteria Nitrobacter (Wang et al., 2004; Metcalf and Eddy, 1991).

Both Nitrosomonas and Nitrobacter (nitrifying bacteria) have lower growth than heterotrophic bacteria, requiring sufficient time to oxidize ammonia to nitrate since the nitrification conversion process requires two-sequential steps to occur. Increasing the HRT provides more contact time for the nitrifying bacteria to perform their metabolic activities, enhancing the nitrification process and improving ammonia removal. According to Kutty et al. (2013), to encourage nitrification, the reactor must operate at a high retention time for the nitrifiers to grow.

These microorganisms increase in aerobic systems due to their ability to utilize oxygen, so in this experiment, aeration in an aerobic reactor was maintained at a constant gas/water ratio of 1/5, controlled by a rotameter, to provide a dissolved oxygen concentration greater than 4.89 mg/L, so that the absence of dissolved oxygen didn't limit nitrification. The result showed that the system could perform better at increasing HRT and reducing NH_4^+ removal. They also concluded that the nitrifying process favors high HRT values since there is enough time for developing nitrifying bacteria active in biofilm.

Effect of different HRTs on the removal of total nitrogen

Figure 6 and Table 6 show how the concentration of total nitrogen input, output, and removal efficiency changes with HRT, while Figure 7 and Tables 7 and 8 show how the bio-contact oxidation reactor removes TN on average. As can be seen in Figures 6 and 7, HRT in the range of 24 to 12 significantly affected TN removal efficiencies. It is clear that when HRT went from 24 to 12,

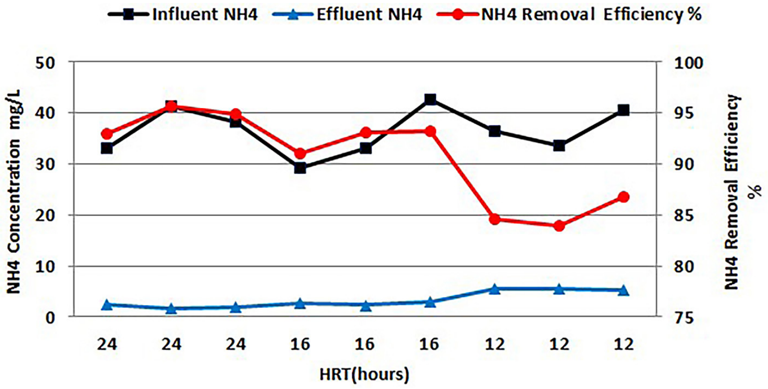

Figure 4. The NH_4^+-N concentration at the inlet, outlet, and removal efficiency at different HRTs

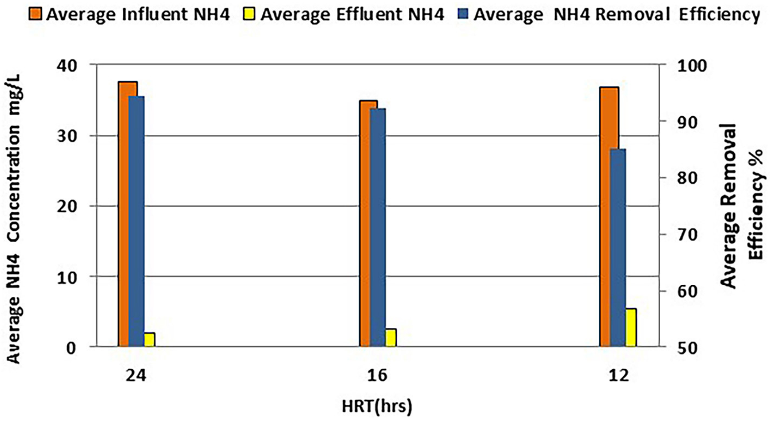

Figure 5. Average NH_4^+-N concentration and average removal efficiency at different HRT

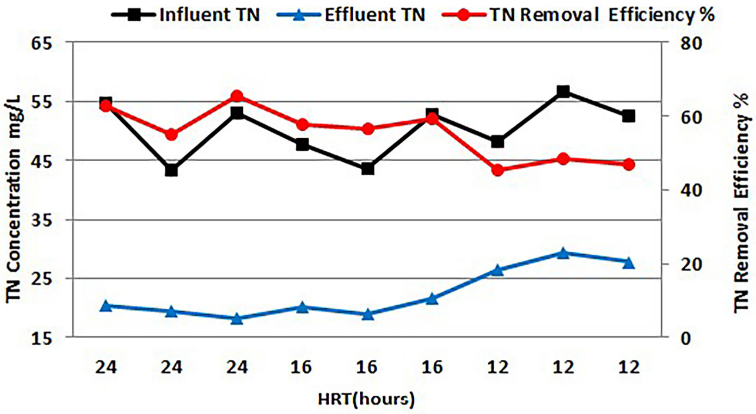

Figure 6. The TN concentration at the inlet, outlet, and removal efficiency at different HRTs

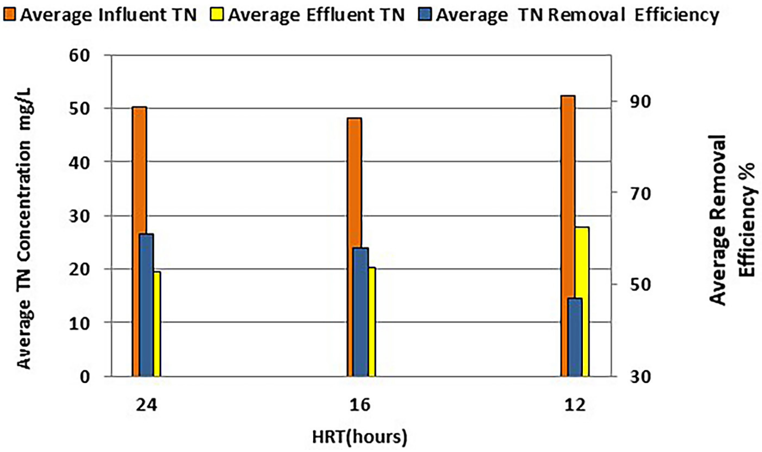

Figure 7. Average concentration of TN and average removal efficiency at different HRT

the average total TN concentration in the effluent went up from 19.43 mg/L (S.D. = 1.06) to 27.84 mg/L (S.D. = 1.44) and the average total removal efficiency went down from 60.98% (S.D. = 5.47) to 46.88% (S.D. = 1.53). Mean TN removals and final concentrations for the 24 h, 16 h, and 12 h were 60.98% (S.D. = 5.47), 19.43 mg/L (S.D. = 1.06), 57.81% (S.D. = 1.35), 20.25 mg/L (S.D. = 1.28), 46.88% (S.D. = 1.53), and 27.84 mg/L (S.D. = 1.44). The data demonstrate that only after 24 hours is the TN removal efficiency in the anoxic-aerobic bioreactors satisfactory.

Effect of different HRTs on the removal of total phosphorus

Figures 8 and 9 and Tables 6 to 8 show the results of TP removal efficiency at different HRTs

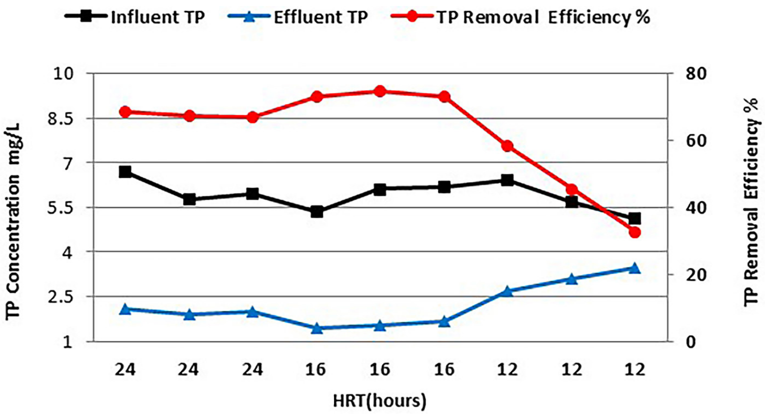

Figure 8. The TP concentration at the inlet, outlet, and removal efficiency at different HRTs

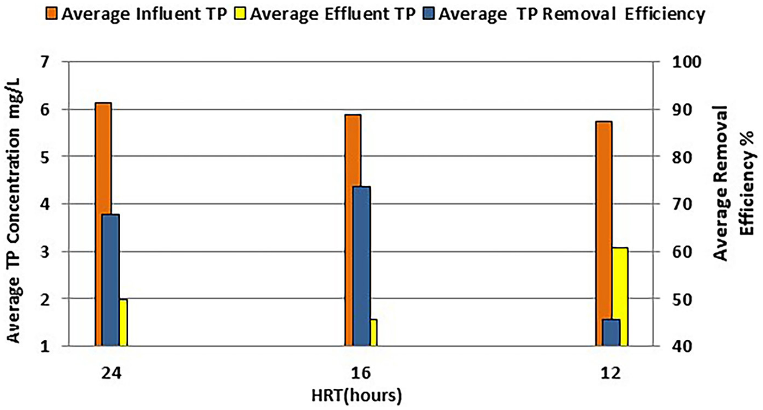

Figure 9. Average concentration of TP and average removal efficiency at different HRT

over the operating time. The change in TRH influenced the removal of TP from the system. However, the average removal of TP was highest at HRT of 16 h, which was 73.48% (S.D. = 1), with a mean final concentration of 1.56 mg/L (S.D. = 0.12). At 24 h of HRT, the average TP elimination was 67.57% (S.D. = 0.91), and the final concentration was approximately 1.99 mg/L (S.D. = 0.11). When the HRT was 12 h, the average removal was 45.48% (S.D. = 12.77), and the final concentration was around 3.07 mg/L (S.D. = 0.39). The results demonstrate that only at 24 and 16 hours do the anoxic-aerobic bioreactors effectively remove TP from the sewage.

CONCLUSIONS

Based on the collected data and experience acquired in the monitoring operation of the experiments over the five months of operation of the bio-contact oxidation system, it is concluded that:

1. The continuous-upflow lab-scale combined anoxic-aerobic bio-contact oxidation reactor was used and showed excellent efficiency for nitrification, denitrification, and organic matter removal from the municipal effluent, whose composition was variable over time. The presence of support materials showed improvements in the efficiency of the system.
2. Concerning removing organic matter, expressed as COD, COD removal percentages were achieved in the 89.92 to 93.51% range when reducing HRT from 12 h to 24 h or change the flow rate. These results show the capacity of the bio-contact oxidation reactor to operate at variable flow rates. Furthermore, it was observed that the COD removal efficiency was little affected by increasing the HRT.
3. About HRT, even with the decrease from 24 h to 12 h, the system achieved high levels of nitrification, with average ammonium removal efficiencies greater than 94.50%.
4. The TN was monitored in the influent and effluent at different HRTs, and an average removal of 60.98% was observed.
5. In terms of phosphorus, there was removal with an average efficiency of 73.48% at 16 h HRT.

In general, the data demonstrated that a HRT of 24 hours is ideal for simultaneous organic and nutrient elimination.

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