



Performance and Energy Consumption Evaluation of Rotating Biological Contactor for Domestic Wastewater Treatment

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ABSTRACT

Biological processes are extensively used for wastewater treatment because of low organic footprint, economically feasible, and high treatment efficiency. Rotating biological contactors (RBC), an attached growth biological process offers advantage of low operating cost, simple configuration and structure, reduced bionomical footprint and thus has been extensively employed for organics and nitrogen removal. In this study, RBC was used for the treatment of synthetic domestic wastewater operating at high hydraulic and organic loading rate to demonstrate the biological performance. The results showed that the RBC achieved a treatment efficiency for COD, ammonium, TN and turbidity of 70.2%, 95.2%, 70%, and 78.9 %, respectively. The efficient nitrogen removal and increased nitrate concentration signify the presence of nitrifying bacteria which actively degrade the nitrogen compounds through the nitrification process. Thus, this system is a sound alternative for both domestic and industrial wastewater treatment for decentralized applications.

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1. INTRODUCTION

The effluent of wastewater treatment processes ought to follow standards to ensure environmental sustainability (Mertens *et al.*, 2018). Several physical, chemical, and biological treatment processes are used for wastewater treatment. All of them have their own merits and limitations (Rajasulochana & Preethy, 2016). High effluent quality is achieved by traditional biological processes, but it gives expenses of high energy usage largely for reactor aeration. It accounts for ~55% of the total energy budget for wastewater treatment (Bilad *et al.*, 2012b). The development of a wastewater treatment technology can further improve effluent quality and increase pollutant removal efficiency (Bilad *et al.*, 2012a).

Secondary wastewater treatment is a biological process that employs an ample variety of microorganisms, primarily bacteria. These microorganisms; contained in wastewater; transform biodegradable organic matter into basic substances and extra biomass. These biological treatment methods are employed worldwide to treat both domestic and industrial wastewater (Waqas *et al.*, 2020). Rotating biological contactors (RBC), a fixed-film process, have been employed for the treatment of domestic, municipal and industrial wastewater (Waqas & Bilad, 2019). Some of the potential advantages of RBC are low land requirement, simple process control, and monitoring, low operating and maintenance costs, high biomass concentration, low excess sludge production, short hydraulic retention time (HRT), high oxygen transfer efficiency, no need of sludge recirculation, process is highly resistant to shock and toxic loads and has a compact design (Cortez *et al.*, 2008; Patwardhan, 2003).

In RBC, large surface area and high biomass concentration facilitate relatively short HRT (Hassard *et al.*, 2015). High oxygen transfer efficiency eliminates the need for

extra aeration. An RBC produces fewer (about 10-20% less) sludge than the conventional activated sludge (CAS) process due to its longer solids retention time resulting in smaller clarifier volume to handle the excess sludge (Williams & Williams, 2011). In the CAS, a portion of the settled sludge is returned from the secondary clarifier back to the aeration tank to meet the required microorganisms in the system (Sodhi *et al.*, 2018). But in RBC, due to the excess of microorganisms, no sludge recirculation is required. Compared to other bioreactors, the RBC is proving effective in treating domestic and industrial wastewaters, mainly because it offers high interfacial area generating in the rotating disks to establish good contact between the microbial species and pollutants (Pakshirajan & Kheria, 2012).

In recent years, RBC has been employed for the treatment of various types of substrates, including municipal wastewater. RBC can undertake chemical oxygen demand (COD) and total nitrogen (TN) removal for domestic and high strength sewage (Hiras *et al.*, 2004; Vlaeminck *et al.*, 2009) and limited enhanced phosphorous recovery (Yun *et al.*, 2004). RBC has been effective to remove toxic chemicals such as toluene, phenol, trichloroethylene and various textile dyes. Organics and nutrients removal have been extensively studied as an efficient treatment process (Waqas & Bilad, 2019). High-strength wastewater such as palm oil mill and poultry effluent has successfully been treated with RBC (Najafpour *et al.*, 2005). RBC is ideal for dye treatment for decentralized treatment applications.

Studies have been conducted to ascertain the effect on RBC performance of factors such as recirculation, disk rotational speed, temperature, hydraulic conditions, presence of organic particulate matter, use of supplemental air and scale-up (Cortez *et al.*, 2008; Hassard *et al.*, 2015). Disk rotational speed affects oxygen transfer to the biofilm for substrate utilization while loading

conditions determine the overall treatment capacity of the bioreactor.

The utility of RBC has been examined at the laboratory scale for organics and nutrient removal from domestic wastewater (Gupta & Gupta, 2001; Hiras *et al.*, 2004). However, the study on the impact of high loading conditions on the biological performance is still lacking. Based on our previous works (Bilad, 2016; Bilad *et al.*, 2016; Bilad, 2017), the present research aims to study the RBC bioreactor for the treatment of synthetic wastewater under high hydraulic and organic loading conditions. After biofilm acclimatization, biological performance in terms of COD, ammonium, TN and nitrate were assessed. Under optimal operating conditions, RBC bioreactor is more energy economical and results in high effluent qualities than CAS and sequencing batch reactor (SBR).

2. MATERIALS AND METHODS

2.1. Wastewater preparation

The activated sludge used to inoculate the lab-scale RBC was obtained from a full-scale domestic wastewater treatment plant. The influent synthetic wastewater was prepared by blending food leftover (as suggested by Kharraz *et al.*, 2015). The prepared feed was filtered to remove the suspended particles and to only set sight on the dissolved matter. The feed solution was prepared by diluting a stock solution to a final concentration as enlisted in **Table 1**. The wastewater characteristics were monitored on a three-day basis to measure COD, ammonium, TN, nitrate, turbidity and pH.

2.2. RBC set-up and operation

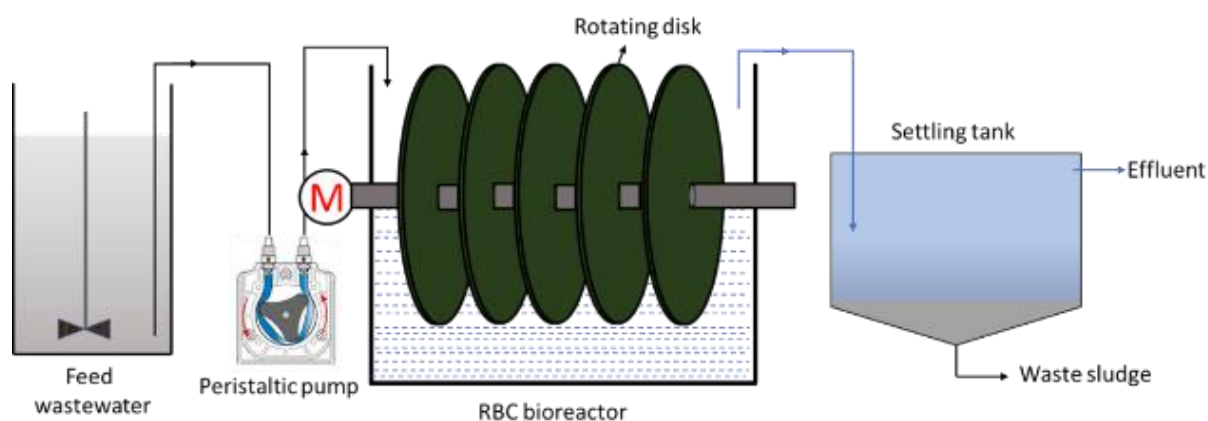
The laboratory-scale RBC comprised a storage tank (volume: 45 L), a bioreactor

(effective volume: 6.5 L), and a solid-liquid separation zone (volume: 10 L) **Figure 1** and **Table 2**. The bioreactor consisted of 5 disks of 1.8 cm thickness and 18 cm diameter separated by a 3 cm gap. The disks were mounted on a single stainless-steel shaft powered by a motor. Polyurethane foam (0.8 cm thickness) was glued to both sides of disks to attach microorganisms and form biofilm for degradation. Disk submergence was fixed at 40% with a 12 ml/min hydraulic loading rate (HLR) to give a 9 h HRT. The bioreactor was operated at a constant organic loading rate (OLR) of 17 g COD/m².d. Peristaltic pumps were installed at the inlet and outlet to provide feed and to withdraw sludge. The rotational direction of discs was cross to the direction of wastewater flow, so this investigation was effected in a cross-flow system with a rotation speed of 30 rpm (Alemzadeh *et al.*, 2002).

The experiment duration was 45 days, divided into two portions. During the first 15 days' time period, the bioreactor was fed to fully acclimatize the biofilm at the rotating polyurethane foam surface. Carbonaceous bacteria responsible for organic removal are fast-growing while nitrifier is accountable for the ammonium removal. Carbonaceous bacteria dominate the bioreactor and take only 3-5 days to fully develop while nitrifying bacteria achieve acclimatization in 14-17 days. A balanced system has an optimum COD/N ratio to establish a mature microorganism biofilm. After the acclimatization stage, the analysis of wastewater was conducted every three days to analyze the effluent quality. In the second stage of the experiment, the bioreactor was operated to study the effect of operational and effluent parameters on biological performance.

Table 1. Typical composition of influent synthetic wastewater

Containments	Unit	Influent
COD	mg/L	262 ± 19
TN	mg/L	2.23 ± 0.03
Ammonium	mg/L	0.63 ± 0.01
Nitrate	mg/L	0.55 ± 0.02
Turbidity	NTU	14.62 ± 0.10
pH	--	6.25 ± 0.03

**Figure 1.** Schematic diagram of conventional RBC unit

2.3. Analytical methods

COD was measured by method 5220D, using the Hach COD digestion solution for low range (3-150 mg/L) by diluting the solution. Ammonium was measured by method 4500- NH₃, using the Hach nitrogen, ammonia digestion solution through the salicylate method for low range (0.02-2.50 mg/L). TN was measured by method 4500-N.C, using the Hach TN through the persulfate digestion method for low range (0.5-25.0 mg/L). Nitrate was measured by method 4500- NO₃, using the Hach chromotropic acid method for high range (0.2-30.0 mg/L). Turbidity and pH were measured using Hach 2100Q portable turbidimeter and Hach HQ411D benchtop PH/MV meter, respectively.

2.4. Scanning electron microscope (SEM) observation

After the acclimatization stage, a 1 cm square of the RBC biofilm was cut for a scanning electron microscopy (SEM) analysis. First, the sample was fixed with formaldehyde impregnation. Then the biofilm sample was dehydrated by immersion in 20, 40, 60, 80 and 100% ethanol to avoid shrinkage and was then followed by drying process. The dried sample was sprayed with gold to increase conductivity using an ion sputter instrument and then observed via SEM. The conductive sample was loaded onto the SEM sample stage under vacuum conditions and electron gun shoots out a beam of high-energy electrons. The signals from electron beam was amplified and sent to a monitor, creating a 3D image.

3. RESULTS AND DISCUSSION

3.1. Biofilm analysis

The biofilm developed at the surface of the disk was characterized using SEM to

visualize the biofilm as shown in **Figure 2**. SEM images were obtained at 40X and 5,000X magnification levels. **Figure 2a** shows a birds-eye view of the biofilm established on the carrier media at 40X magnification. The results of SEM show the well-established biofilm of microorganisms at the media surface. The five stages of biofilm growth are; single free-floating bacteria land on the surface, bacterial cells aggregate and attach, growth and division of bacteria for biofilm formation, mature biofilm formation, and part of biofilm disperses to release free-floating bacteria for further colonization. After the acclimatization phase, the biofilm is completely developed and effectively undertake the organics removals. A mature biofilm with characteristic mushroom formed of polysaccharide can be seen in **Figure 2b**. At this stage, cells starting to detach, reverting to planktonic cells which stick to the new surface to develop another biofilm layer.

3.2. Loading and test conditions

Table 3 shows the comparison of the average loading rates and general control data for the present RBC reactor with one previous study. The dissolved oxygen (DO)

concentration remained at an elevated level in the aerobic unit and pH was in the appropriate range for the biological processes involved. The OLR to the aerobic bioreactor averaged 9.2 (3.4-18) g/m².d; much higher values of OLR (17 g/m².d) was applied in the current study. The HLR to the aerobic bioreactor averaged 44 (27-68) L/m².d (Hiras *et al.*, 2004); the current study HLR of 68 L/m².d indicates the robustness of the process maintaining sufficiently high removal efficiencies. The selection of media imparts a crucial role in increasing the microbial community to increase the OLR and HLR.

3.3 COD removal

Figure 3 demonstrates the variations in COD values for the RBC influent, effluent and removal efficiency. The average removal efficiency of 70.2 ± 1.3% was obtained with no significant difference after the acclimatization period. The average effluent COD concentration was 82 ± 6 mg/L at the 9 h HRT and 17 g COD/m².d OLR shows significant bioreactor performance. The RBC had lower effluent COD concentrations indicating high carbonaceous bacteria biofilm development at the media disk.

Table 2. Design specification for laboratory-scale RBC unit

MRBC design parameters	Unit	Number/Sizing
Length of unit	cm	25
Width of unit	cm	25
Height of unit	cm	30
Material used for fabrication	-	Acrylic
Material of the disks	-	Acrylic
Diameter of disk	cm	18
Thickness of disk	cm	1.8
Spacing between the disks	cm	3
Number of disks	Nos.	5
Shaft diameter	mm	8
Motor type used	-	DC motor
Motor speed	rpm	30

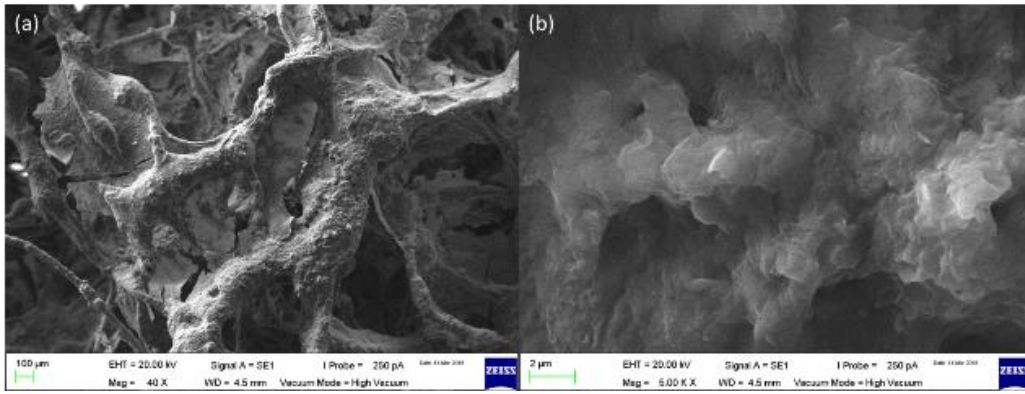


Figure 2. SEM results of biofilm developed at the surface of the rotating disk

Table 3. Loading and test conditions

Operation or loading value	Aerobic RBC (Hiras et al., 2004)	This study
pH	7.1-8.1	6.2
Hydraulic loading rate, L/m ² .d	44 (27-68)	68
Organic loading rate, g COD/m ² .d	9.2 (3.4-18)	17
Temperature, °C	11.6-19	17.2

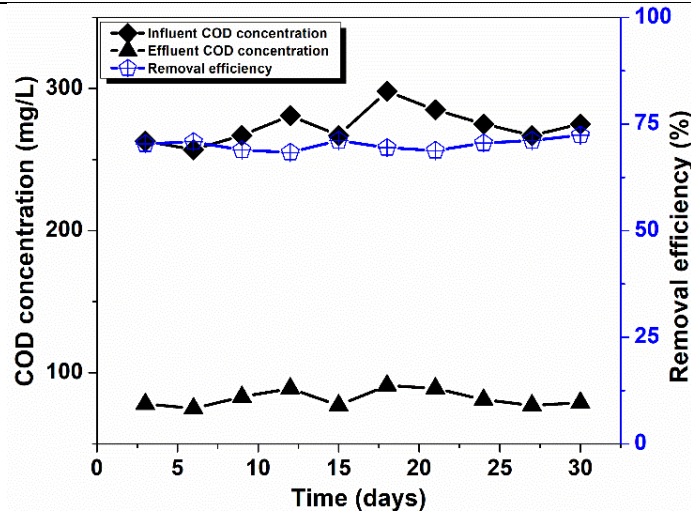


Figure 3. Influent and effluent COD concentration and removal efficiency against time

Carbonaceous bacteria are responsible for the removal of COD hence, efficient removal indicates its sufficient content in the bioreactor. The COD reduction in the effluent indicates the continuously consumed of the influent organic matter by the microorganisms attached to the disk surface. Although the RBC bioreactor was operated at high organic loading and hydraulic loading, it still exhibits significant removal efficiency of COD removal. The COD removal efficiency is high enough to satisfy the treatment requirement for municipal wastewater.

Wastewater with high organic content favours carbon removal through both aerobic and anaerobic processes. Due to the media disk rotation, RBC sustains high DO concentration maintaining high biomass activity Continuous interaction of media disk and substrate results in high removal efficiency even at high OLR and HLR conditions (Pan et al., 2017).

A study by Han et al. (2019) operated RBC at 40% submergence and 8 h HRT results in 88.1 ± 3.2% COD removal efficiency. Another study by Kiran et al. (2017) results

in a COD removal efficiency of 68-82% at 40% disk submergence, and 48 h residence time. This reveals that the COD removal efficiency is dependent on the operating condition (disk rotational speed, HRT, organic loading rate, disk submergence) and influent wastewater strength. Together with the attached biomass, the suspended sludge present in the bioreactor due to biofilm slaughtering further improves the substrate removal efficiency, in terms of COD removal (Kiran *et al.*, 2017).

3.4. Nitrogen removal

Nitrification; an aerobic process; is a two-step process, oxidation of ammonium to nitrite through ammonia-oxidizing bacteria (AOB) and then conversion of nitrite to nitrate through nitrite-oxidizing bacteria (NOB) (Vázquez-Padín *et al.*, 2010). **Figure 4a** demonstrates the summary of the TN removal performance for the RBC bioreactor. The RBC bioreactor achieves an overall TN removal efficiency of 70.0 ± 1.2 % with effluent values at 0.75 ± 0.03 mg/L with no significant changes during the entire study period. Ammonium in the synthetic wastewater comes from ammonia dissolved in water. The RBC bioreactor achieves 95.2 ± 0.06 % ammonium removal efficiency with very low effluent concentration 0.03 mg/L **Figure 4b**. The nitrate content of the influent wastewater is low but an increase in the nitrate content is observed at the RBC effluent. The nitrate concentration is the effluent increases constantly and reaches a maximum value of 1.9 ± 0.03 mg/L **Figure 5**. The nitrate can be converted to nitrogen gas under anaerobic conditions called denitrification.

High ammonium removal efficiencies indicate the presence of AOB and NOB bacteria activity reducing the ammonium to

nitrite and nitrate. The absence of anoxic conditions renders further nitrogen removal, however, DO deprived condition can be observed in the lower part of the bioreactor due to non-linear mixing hence promoting the denitrification process. The low effluent values of ammonium indicate the presence of nitrifying microorganisms. On the other hand, denitrification is an anaerobic process requiring low DO concentration. Due to the aerobic nature of the process, denitrification cannot be achieved but slight denitrification can occur at the bottom of the bioreactor due to the limited supply of air to the settled sludge.

The domestic wastewater is considered as nitrogen-limited for nitrifying biomass growth, effective mineralization and even nitrification processes occurred in the RBC bioreactor without encountering any problem. This is due to the fact that biofilm processes have low biomass yield and very high sludge retention time (Abdel-Kader, 2013). The current study also demonstrates the limited influent nitrogen concentration but thanks to the high SRT and low biomass yield, the system attains significant nitrogen removal efficiency.

The results indicate that the reactor achieved complete nitrification where most of the ammonium was converted to nitrate. Wang *et al.*, (2018) utilized non-woven RBC to achieve TN removal efficiency of 79.1% under low DO of 0.2-0.8 mg/L, mainly through simultaneous partial nitrification, anaerobic ammonium oxidation, and denitrification pathways. Therefore, the balanced adjustment of nitrification and denitrification rates, by rotational speed, submergence level, and biofilm thickness, etc., could be controlled to improve the TN loss at the bioreactor. It is concluded that RBC can effectively reduce the TN content from municipal wastewater.

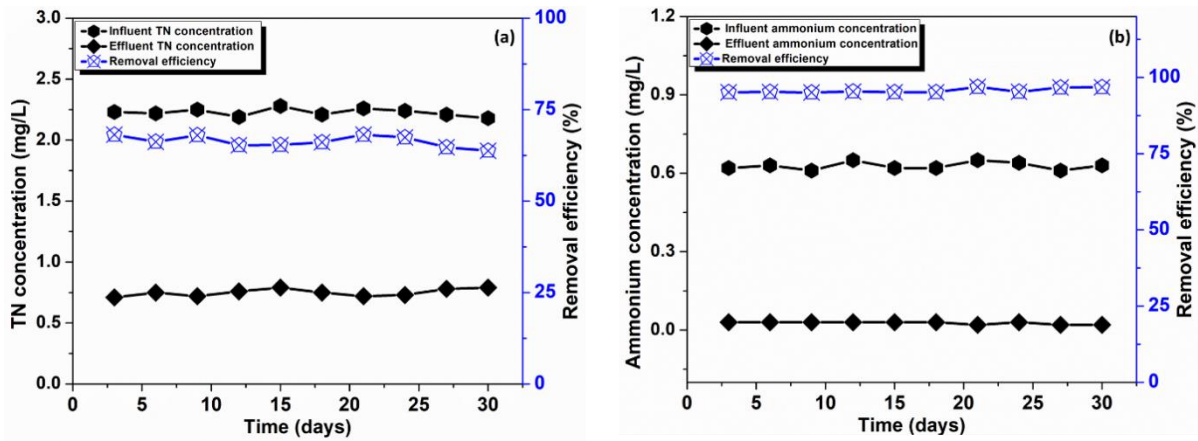


Figure 4: (a) Influent and effluent TN concentration and removal efficiency against time and (b) Influent and effluent ammonium concentration and removal efficiency against time

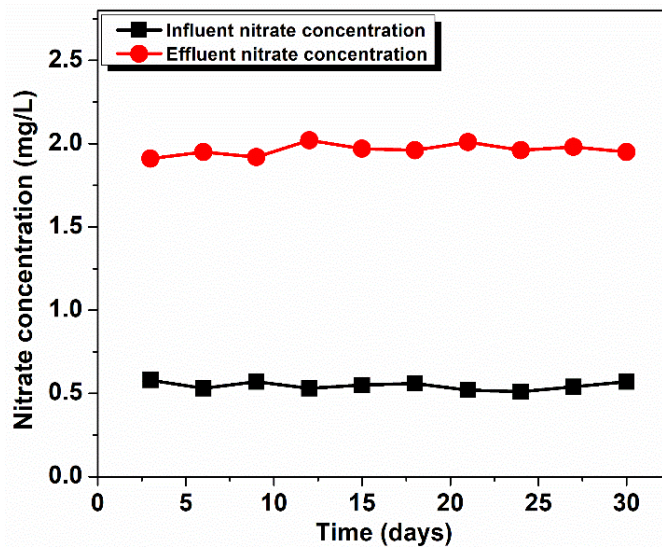


Figure 5: Influent and effluent nitrate concentration against time

Some reports have reported that RBC has the capacity of aerobic denitrification. Due to the lower DO concentration at the bottom of the bioreactor than on the surface, the bottom of the RBC is considered as an important place where denitrification took place (Zha et al., 2018). However, a high C/N ratio and lower TN values restrict the nitrifying bacteria growth and thus reduce the denitrification process. The system obtains a relatively lower TN removal because of lower influent quantities and strong competition between heterotrophic and autotrophic bacteria.

3.5. Turbidity removal

Figure 6 shows the influent and effluent turbidity along with removal efficiency throughout the experimentation duration. The RBC effluent turbidity values remain at 3.1 ± 0.06 NTU with average removal efficiency at $78.9 \pm 0.3\%$. A steady removal efficiency has been observed throughout the experimentation indicating the smooth operation and optimized operating conditions. However, this study only demonstrates constant disk rotational speed and organic and hydraulic loading, the effect of these parameters requires further experimentation. The effluent turbidity values can be increased by installing sand filtration after the settling tank.

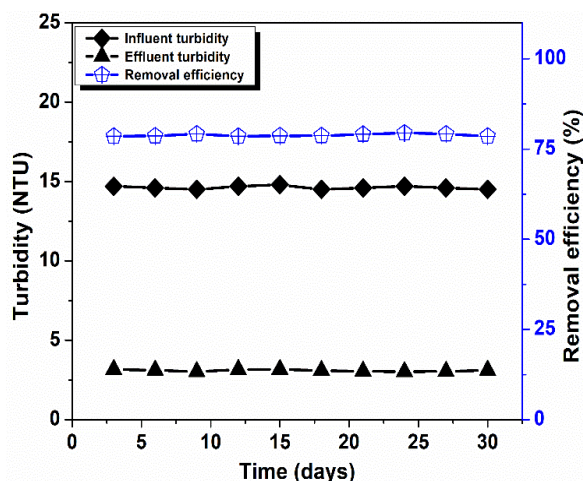


Figure 6. Influent and effluent turbidity and removal efficiency against time

3.6 Energy requirement

The energy requirement of the RBC on the average was calculated as about 1.2 kWh/m³ of wastewater treated (Abdel-Kader, 2013). On the other hand, the corresponding energy requirement obtained for domestic wastewater treatment by MBR and SBR was calculated to be 1.7 kWh/m³ and 3.6 kWh/m³, respectively. Hence, the energy requirement of the domestic wastewater treatment by RBC is lower than the MBR and SBR (Atasoy *et al.*, 2007; Baban *et al.*, 2010). The reported energy consumption for RBC is highly attractive compared to the CAS for wastewater treatments.

The RBC effluent quality mostly complied with the reuse criteria of EPA suggested guidelines for urban reuse including toilet flushing. However, biofilm detachment due to the imparted shear rate generated by the rotating media disk occasionally results in higher total suspended solids and turbidity values. The detached biofilm layer does not settle easily and hence decreases the effluent quality. To fulfil the standard effluent guidelines, a simple sand filtration unit is recommended before disinfection.

A potential disadvantage to increase rotational speed is the power consumption of the RBC units, proportional to the square of rotations per minute at pilot-scale (Watanabe *et al.*, 1993). Therefore,

decreasing the rotational speed may offer the advantage of lower operational cost because of the decreased workload by the motor and hence reduced energy consumption (Ramsay *et al.*, 2006). This could, however, have the opposite effect on oxygen availability and nutrient mass transfer and lead to decreased treatment potential.

In comparison to MBR, RBC attains lower organics and nutrient removal efficiencies, however, high energy and maintenance costs in MBR hinder the widespread application for decentralized plants. RBC comprise a promising method for domestic wastewater treatment for use, considering low operation and maintenance cost, ease of operation, and provision of sufficient effluent quality (Baban *et al.*, 2010). The relatively simple design of RBC promises a platform for decentralized energy efficient wastewater treatment. A variety of RBC have been applied for energy generation through algae and biogas. Careful media selection could enhance microbial growth to increase the OLR and organics and nutrients removal. Although RBC may possess some inherent drawbacks (Bilad *et al.*, 2020), the benefits of low energy consumption, ease of operation, and sufficiently high effluent quality are indeed promising.

4. CONCLUSION

The high effluent quality of RBC operating at a high OLR and HLR proved the robustness of the process. The results indicated that the average COD, ammonium, TN, and turbidity concentration of effluent were 82 ± 6 mg/L, 0.03 ± 0.01 mg/L, 0.75 ± 0.03 mg/L, and 3.1 ± 0.06 NTU and removal efficiencies of 70.19%, 95.16%, 70%, and 78.86%, respectively. The energy requirement analysis for RBC depicts that it consumes less energy compared to other biological treatment processes (MBR and SBR). The operating advantages and low energy consumption prove its effectiveness for municipal wastewater treatment.

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6. AUTHORS' NOTE

The author(s) declare(s) that there is no conflict of interest regarding the publication of this article. Authors confirmed that the data and the paper are free of plagiarism.

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