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Effect of Operating Parameters and Energy Expenditure on the Biological Performance of Rotating Biological Contactor for Wastewater Treatment

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Citation: Irfan, M.; Waqas, S.; Khan, J.A.; Rahman, S.; Kruszelnicka, I.; Ginter-Kramarczyk, D.; Legutko, S.; Ochowiak, M.; Włodarczak, S.; Czernek, K. Effect of Operating Parameters and Energy Expenditure on the Biological Performance of Rotating Biological Contactor for Wastewater Treatment. *Energies* **2022**, *15*, 3523. https://doi.org/10.3390/en15103523

Academic Editors: Redmond R. Shamshiri, Muhammad Wakil Shahzad, Muhammad Sultan and Md Shamim Ahamed

Received: 28 March 2022
Accepted: 8 May 2022
Published: 11 May 2022

Abstract: The rotating biological contactor (RBC) is resistant to toxic chemical and shock loadings, and this results in significant organic and nutrient removal efficiencies. The RBC system offers a low-energy footprint and saves up to 90% in energy costs. Due to the system's low-energy demand, it is easily operable with renewable energy sources, either solar or wind power. An RBC was employed to degrade pollutants in domestic wastewater through biodegradation mechanisms in this study. The high microbial population in the RBC bioreactor produced excellent biological treatment capacity and higher effluent quality. The results showed that the RBC bioreactor achieved an average removal efficiency of 73.9% of chemical oxygen demand (COD), 38.3% of total nitrogen (TN), 95.6% of ammonium, and 78.9% of turbidity. Investigation of operational parameters, disk rotational speed, HRT, and SRT, showed the biological performance impact. Disk rotational speed showed uniform effluent quality at 30–40 rpm, while higher values of disk rotational speed (>40 rpm) resulted in lower effluent quality in COD, TN, and turbidity. The longer hydraulic retention time and sludge retention time (SRT) facilitated higher biological performance efficiency. The longer SRTs enabled the higher TN removal efficiency because of the higher quantity of microbial biomass retention. The longer SRT also resulted in efficient sludge-settling properties and reduced volume of sludge production. The energy evaluation of the RBC bioreactor showed that it consumed only 0.14 kWh/m^3, which is significantly lower than the conventional treatment methods; therefore, it is easily operable with renewable energy sources. The RBC is promising substitute for traditional suspended growth processes as higher microbial activity, lower operational and maintenance costs, and lower carbon foot print enhanced the biological performance, which aligns with the stipulations of ecological evolution and environment-friendly treatment.

Keywords: wastewater treatment; biological process; aerobic process; attached growth; biofilm; rotating biological contactor

1. Introduction

Nowadays, the world is facing a major issue, which is freshwater availability. There is no availability of potable water for about one-sixth of the total population of the world. An enormous quantity (30–70 mm^3) of wastewater per person per year is generated by industries and cities of developing countries [1,2]. Due to these problems, industries have to solve serious issues to meet the rigorous wastewater removal requirements [1,3]. Therefore, attention has been paid to the rotating biological contactor (RBC). The RBC has emerged as a low-energy-consuming technology used in wastewater treatment which compares favorably with other treatment methods [4].

The RBC is a fixed-film bioreactor employing rotating discs to provide a support medium for microbial growth and supply dissolved oxygen. The advantages of RBCs over other attached growth systems include, but are not limited to, being able to handle high hydraulic and organic loading rates, being resistant to shock loadings, having low area and maintenance requirements and low-energy demand and operational costs, being able to handle specific contaminants, e.g., hydrocarbons, textile dyes, colored wastewater, heavy metals, and xenobiotics, and being able to produce energy through the anaerobic process along with wastewater treatment [5–9]. The RBC bioreactor characterizes a practical source for nitrification and denitrification processes as the microbial biomass is abundant and stable [10–12]. Nitrifying bacteria responsible for nitrification are one of the major microorganisms in the biofilm. Previous literature has shown that the RBC has successfully treated domestic, municipal, and industrial wastewater [13,14].

The operational parameters influencing the functioning of the RBC bioreactor, such as disk rotational speed, hydraulic retention time (HRT), sludge retention time (SRT), and carrier media type have been extensively reported [15,16]. The selection and optimization of parameters strictly depend on the influent wastewater and effluent quality requirements. Disk rotational speed is an important parameter for acclimatizing the microorganisms and developing a full-grown biofilm to digest the organics and nutrients at the carrier surface. It is also responsible for maintaining sufficient dissolved oxygen (DO) levels inside the bioreactor to facilitate the degradation process [17,18]. The selection of SRT and loading rates relies on the wastewater strength and effluent requirements. A short SRT only facilitates carbon deduction, whereas a longer SRT results in increased sludge concentration hindering the oxygen transfer [19].

Microbial community characteristics are highly dependent on the selected disk rotational speed, SRT, DO levels, and microorganisms present in the bioreactor [20,21]. Carbonaceous and ammonia-oxidizing bacteria (AOB) are aerobic and cultivate in the outer layers of the biofilm, while nitrite-oxidizing bacteria (NOB) dominate the inner parts of the biofilm where anoxic or anaerobic conditions prevail [22]. The competition between the carbonaceous bacteria, AOB, and NOB depends on the influent wastewater and other operating conditions [23]. The results of previous studies have shown that both disk rotational speed and SRT influence biological performance.

Disk rotational speed, HRT, and SRT are significant parameters influencing the performance of the RBC bioreactor. In the present study, to determine the biological performance of domestic wastewater, the effect of disk rotational speed, HRT, and SRT on the chemical oxygen demand (COD), total nitrogen (TN), and turbidity were investigated. The objective of the current study was to explore the biological performance of the RBC bioreactor treating domestic wastewater, focusing on the effect of disk rotational speed, HRT, and SRT.

2. Materials and Methods

2.1. Wastewater Preparation and Bioreactor Acclimatization

The domestic wastewater was prepared by blending food left over from the campus canteen, as described in our previous research [24]. The blended mixture was left for 2 h to settle the suspended particles. The supernatant was then filtered through Whatman filter paper (Grade 1 Qualitative Filter Paper Standard Grade, GE Whatman, Kent, UK). The filtered solution was then diluted to meet the domestic wastewater concentration. The prepared wastewater was analyzed to determine the COD, TN, total Kjeldahl nitrogen (TKN), ammonium, turbidity, pH, and nitrate, as shown in Table 1 [25].

Table 1. Properties of influent wastewater.

Sr #	Contaminant	Unit	Concentration
1	COD	mg/L	281 ± 8.5
2	Ammonium	mg/L	0.66 ± 0.03
3	TN	mg/L	2.5 ± 0.19
4	TKN	mg/L	0.91± 0.09
5	Nitrate	mg/L	0.49 ± 0.04
6	Turbidity	NTU	14.6 ± 0.55
7	pH	–	6.28 ± 0.21

2.2. Bioreactor Set-Up

The RBC bioreactor was operated in accordance with the layout depicted in Figure 1. The bioreactor consisted of a 45 L storage tank, a 6.5 L bioreactor, and 6 L settling tank. The feed wastewater from the storage tank was constantly pumped with a peristaltic pump to the RBC bioreactor. The RBC bioreactor with 25 × 25 × 30 cm dimensions was fabricated in-house with methyl methacrylate sheets. In the RBC bioreactor, five disks fabricated from methyl methacrylate sheets with 18 cm diameter were attached to a stainless-steel shaft. The disks were attached to polyurethane sheets (1.22–1.27 g/cm^3 density) to colonize the microbial population. The polyurethane-coated disks, 3 cm apart from each other (corresponding to a net surface area of 2034 cm^2), were placed inside the RBC bioreactor at 40% submergence. The wastewater from the storage tank was fed continuously to the RBC bioreactor, and treated effluent was transferred to the settling tank. A mechanical stirrer continuously stirred the feed wastewater at 100 rpm to keep the concentration uniform. In the settling tank, sludge settled at the bottom of the tank, and was removed frequently while clear effluent flowed out from the top.

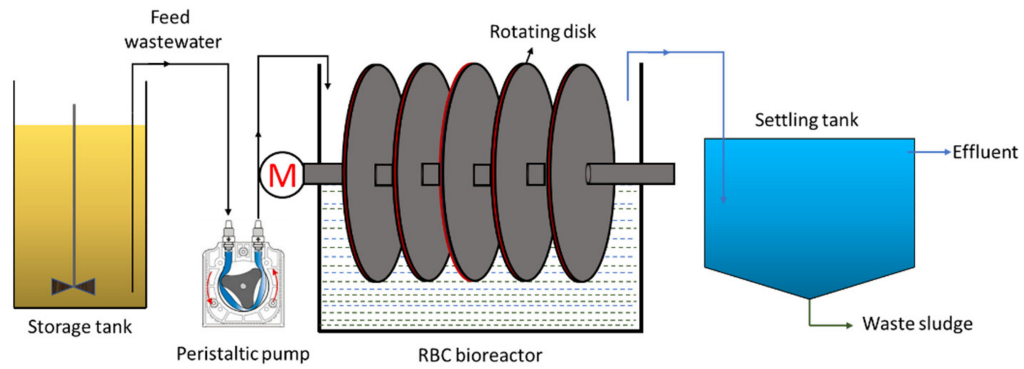

Figure 1. Schematic diagram of RBC configuration.

2.3. Bioreactor Operation

During the acclimatization phase, the operational parameters were constant at 30 rpm disk rotational speed, 9 h HRT, and 15 d SRT. The biofilm layer was observed daily while effluent wastewater concentration was checked every three days. After completing the first phase of the experiments, the bioreactor achieved a steady-state effluent concentration. After biofilm acclimatization, the system was investigated for the effect of disk rotational speed, HRT, and SRT on effluent wastewater. The organic loading rates were kept constant throughout the experiments. The disk rotational speed was increased from 30 to 50 rpm with an interval increase of 5 rpm, while SRT was increased from 5 to 15 d with an interval increase of 2.5 d. The SRT was set by wasting a calculated amount of sludge from the bioreactor each day.

2.4. Analytical Methods

COD, TN, TKN, ammonium, and nitrate were measured using each compound's specific Hach digestion solution (HACH, Loveland, CO, USA). The solution was diluted to fall into the range of the digestion vials being used for the study. The values were determined through Hach DR3900 Spectrophotometer (HACH, Loveland, CO, USA). A Hach 2100Q portable turbidimeter (HACH, Loveland, CO, USA) and Hach HQ411D benchtop PH/MV meter (HACH, Loveland, CO, USA) were used to determine turbidity and pH, respectively [25].

2.5. Scanning Electron Microscope

After the acclimatization stage, a 1 cm^2 piece of biofilm was analyzed using SEM analysis. The biofilm sample was carefully cut from the rotating disk. The foam was then treated with formaldehyde for biofilm impregnation according to the method detailed earlier [26] to maintain the biofilm structure. The biofilm sample was then dehydrated by consecutive immersions in 20, 40, 60, 80, and 100% ethanol solution, each step for 5 min, to avoid shrinkage, followed by a drying process. The dried non-conductive sample was sprayed with conductive gold nanoparticles using an ion-sputter instrument to create a conductive layer on the sample that reduced thermal damage, inhibited charging, and improved the secondary electron signal required for topographic examination in the SEM. The conductive biofilm sample was loaded onto the SEM sample stage under vacuum conditions and an electron gun shot out a beam of high-energy electrons.

2.6. Energy Estimation

The energy consumption of the RBC bioreactor was estimated using an estimation method proposed elsewhere [27]. The RBC treatment capacity is supposed to be the same as that of the referenced bioreactor to evade the effect of plant capability on the energy estimation. Some energy values, such as wastewater pre-treatment, influent pumping, and sludge disposal were assumed constant to depict a fair comparison [28]. The activated-sludge process and MBR utilize coarse-bubble aeration to maintain DO concentration in the bioreactor, accounting for 30–50% of total energy consumption [29]. On the other hand, the RBC bioreactor utilizes disk rotation to maintain DO levels. The energy for shaft rotation was projected from the RBC bioreactor data. The energy contribution of the RBC bioreactor was compared with an optimized referenced MBR with an overall energy consumption of 0.64 kWh/m^3.

The energy consumption for pre-treatment of wastewater (0.02 kWh/m^3) was assumed to be similar to the referenced treatment system. The influent (0.03 kWh/m^3) and effluent (0.02 kWh/m^3) pumping energy demand were also assumed similar because the influent and effluent pumping has no relation to the biological treatment. However, due to system differences and mode of operation, some energy factors, for instance, sludge recycling, coarse-bubble aeration, mixers, bioreactor aeration, and air compression, were not present in the RBC bioreactor.

The major energy requirement of the RBC is the mechanical energy for rotation. The energy for mechanical rotation of the disk was estimated based on the full-scale date of the RBC plant reported elsewhere [27]. The energy consumption was estimated through the energy consumed by the shaft. The shaft energy is a function of flowrate and media surface area. The mechanical energy for shaft rotation is a function of plant capacity and increases exponentially with capacity. The shaft rotation energy was projected using Equations (1) and (2):

$$E_{MR} = \frac{NE_S}{V_O} \tag{1}$$

$$N = \frac{V_O}{H_O A_S} \tag{2}$$

where, E_{MR} is the energy for mechanical rotation (kWh/m^3), N is the total number of shafts, E_S is the energy consumption/shaft (kWh), V_O is the influent flow rate (1774 m^3/h), H_O is the hydraulic loading (gpd/ft^2), and A_S is the media surface area/shaft (m^2).

3. Results and Discussion

3.1. Biofilm Analysis

Figure 2 shows the biofilm developed at the surface of the disk visualized using SEM. The SEM images were obtained at 40× and 5000× magnification levels. Figure 2a shows a birds-eye view of the biofilm established on the carrier media at 40× magnification. The SEM images show the well-established biofilm of microorganisms at the media surface. It can be identified as a mature biofilm that occupied all the sponge media surface. Its excellent biological performance in removing organics from the wastewater detailed in Section 3.3. A mature biofilm with characteristic mushroom formed of polysaccharides can be seen in Figure 2b. At this stage, cells were starting to detach, reverting to planktonic cells that stuck to the new surface to develop another biofilm layer.

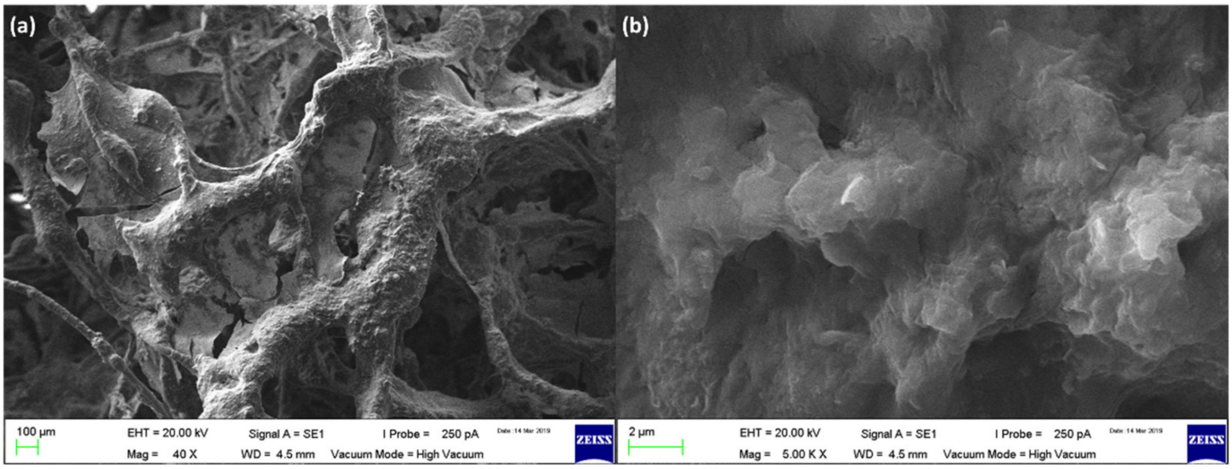

Figure 2. SEM results of biofilm developed at the surface of the rotating disk; (**a**) at 40× and (**b**) at 5000× resolution.

3.2. Biological Performance

Figure 3 and Table 2 show the biological performance in terms of COD, TN, TKN ammonium, and turbidity removal for the 30 d operation of the bioreactor. After biofilm acclimatization, the bioreactor was operated for 30 d to witness the organics and nutrient removal. The RBC bioreactor maintained an average COD removal efficiency of 73.93% with 73.4 mg/L effluent concentration at 9 h HRT and 30 rpm disk rotational speed. The removal efficiency of 38.3% with 1.54 mg/L effluent was obtained for TN, while 95.6% with 0.03 mg/L effluent was obtained for ammonium. The RBC bioreactor significantly reduced the turbidity values, and an average effluent value of 3.1 NTU was obtained with 78.9% removal efficiency. Significant removal efficiencies show the effectiveness of the RBC bioreactor for the treatment of domestic wastewater.

Carbonaceous bacteria are responsible for COD removal, while nitrifying bacteria undergo nitrification. The RBC bioreactor is an aerobic biofilm process with a high DO concentration (8–10 mg/L). Carbonaceous bacteria are heterotrophic and acclimatize in 3–5 d under aerobic conditions. The outer layer of the rotating disks was abundant in carbonaceous bacteria. The substrate from the influent wastewater encountered the microorganisms, and degradation occurred at the disk surface.

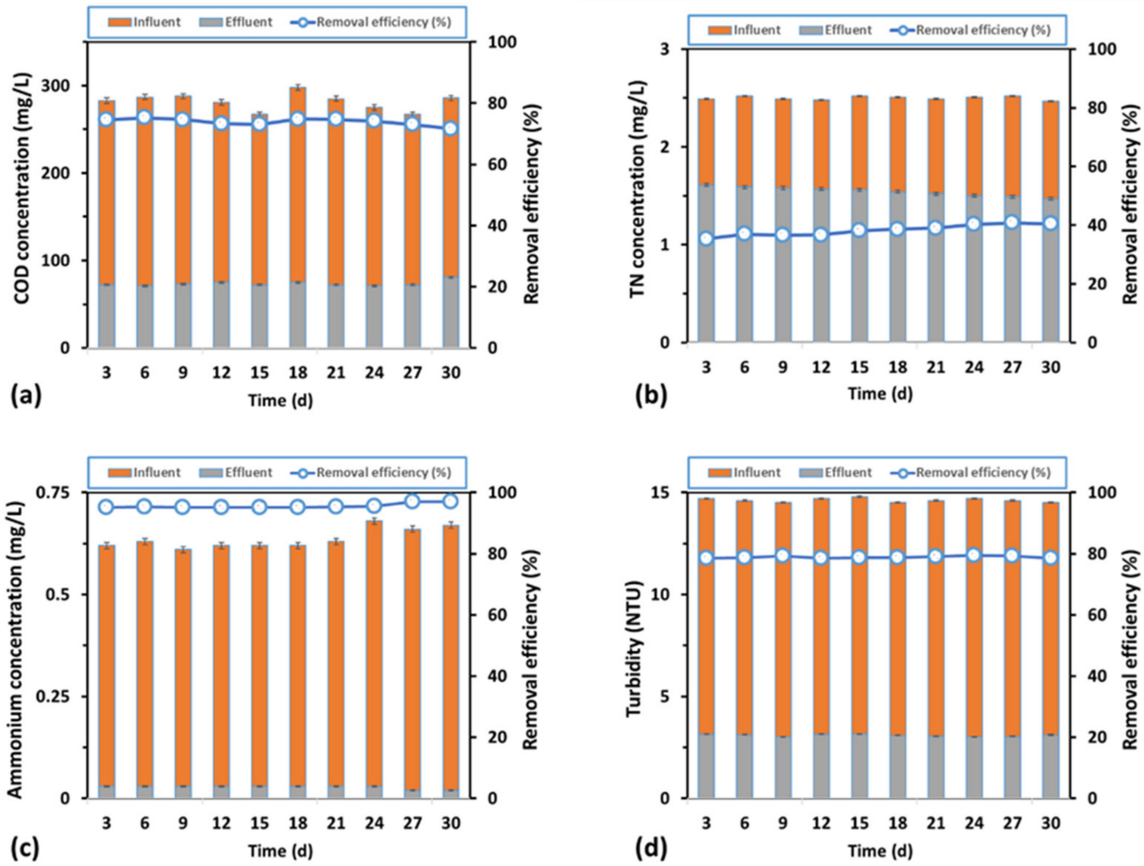

Figure 3. Influent, effluent, and percentage removal efficiency over time of (**a**) COD, (**b**) TN, (**c**) ammonium, and (**d**) turbidity.

Table 2. Properties of effluent wastewater.

Sr #	Contaminant	Unit	Concentration
1	COD	mg/L	73.4 ± 3.0
2	Ammonium	mg/L	0.03 ± 0.0
3	TN	mg/L	1.54 ± 0.05
4	TKN	Mg/L	0.05± 0.01
5	Nitrate	mg/L	1.36 ± 0.07
6	Turbidity	NTU	3.09 ± 0.06
7	pH	–	7.35 ± 0.11

The results showed a high COD removal efficiency during the experiments, with average effluent values higher than 73%. Despite the minor alternations of the feeding COD, the bioreactor exhibited an acceptable activity of the biological consortium. The above COD removal efficiency agreed with what was achieved by [28], who found a COD removal efficiency close to 75% in a similar bioreactor. A slight variation could be explained by the fact that both bioreactors were operated at different SRT. The attained results underline the robustness of the RBC bioreactor regarding COD removal.

The attained results emphasize the ammonium removal efficiency of the bioreactor, with values higher than 95% for most of the experiments. The presence of nitrifying bacteria and favorable aerobic conditions enhanced ammonium oxidation conversion to nitrite and nitrate. The bioreactor maintained a constant effluent concentration of 0.03 mg/L depicting an abundance of nitrifying bacteria activity.

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) [30]. The RBC developed abundant AOB and NOB throughout the biofilm along with carbonaceous bacteria. The RBC exhibited excellent ammonium-removal efficiency throughout the experimentation period. In wastewater with a high organics concentration, heterotrophic bacteria significantly diminish the growth of nitrifiers. Therefore, nitrification occurs after organics removal during the last stage of the RBC bioreactor [31].

The system obtained TN removal efficiency values higher than 38%. The RBC bioreactor maintained a high DO concentration due to the disk-rotation mechanism. The conversion of nitrate into the quasi-inert gases, nitrogen and nitrous oxide, by microbial oxidation of organic matter is called denitrification. High nitrate concentration indicates the absence of anoxic and anaerobic conditions in the bioreactor [32]. However, it is understood that deep inside the biofilm, anoxic conditions prevail due to the DO-concentration-gradient profile. A low C/N ratio also hinders the growth of nitrifying bacteria as carbonaceous bacteria outranks nitrifying bacteria in terms of feed availability [33]. The obtained results showed an average turbidity removal efficiency of more than 78%, indicating high microbial activity. The resultant higher removal efficiency of turbidity indicates excellent sludge-settling properties.

3.3. Effect of Disk Rotational Speed

Figure 4 shows the effect of disk rotational speed on the COD, TN, and turbidity removal from the wastewater. Disk rotational speed, being an important RBC parameter, controls the DO concentration. Higher DO concentration favors biological activity; however, excessive disk rotation will increase energy demand. Higher disk rotational speed also generates shear that shreds off the attached biofilm. The detached biofilm remains suspended and does not easily settle. Excessive shear generation can result in loss of complete microbial activity and washout of microbial biomass from the bioreactor. The bioreactor was operated at constant 9 h HRT and 15 d SRT to study the effect of disk rotational speed.

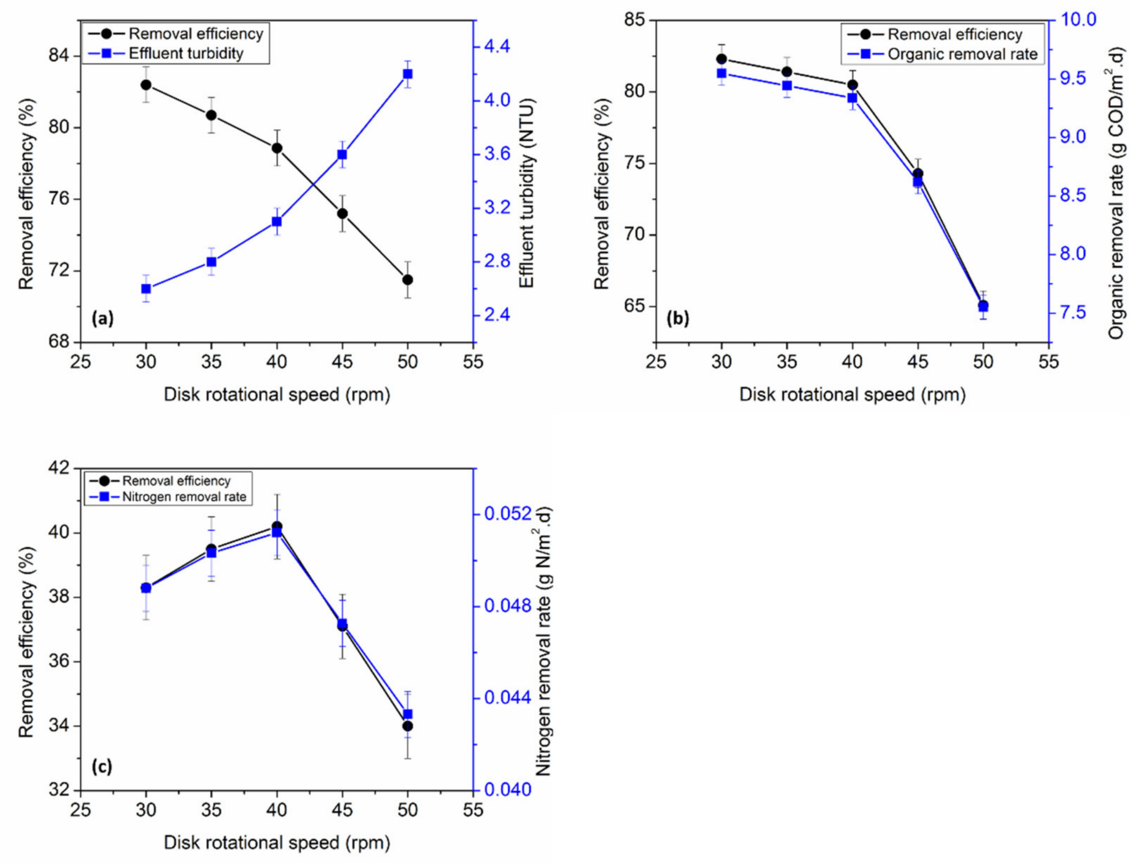

Figure 4. Effect of disk rotational speed on (**a**) turbidity, (**b**) COD, and (**c**) TN removal.

Figure 4a depicts the relationship of effluent turbidity and removal efficiency with the disk rotational speed. The detached floc floats at a higher disk rotational speed and does not settle easily, increasing the effluent turbidity value [22,34]. Lower COD removal efficiency and organic removal rate were obtained at higher disk rotational speed. The bioreactor maintained a constant COD removal efficiency and removal rate as disk rotational speed increased for 30 to 40 rpm. However, a significant change was observed in COD removal efficiency as disk rotational speed increased from 40 to 50 rpm, validating the part of boosted shear rate by the disk rotation. Similar results were obtained for the TN removal efficiency. The bioreactor maintained a constant TN removal efficiency and nitrogen removal rate as rotational speed boosted from 30 to 40 rpm. Further rise in disk rotational speed generates an enhanced shear rate that deteriorates the biofilm and lowers TN removal efficiency.

3.4. Effect of Sludge Retention Time

Figure 5 demonstrates the influence of SRT on the COD, TN, and turbidity removal efficiency. Figure 5a depicts the impact of SRT on turbidity removal efficiency and effluent turbidity. The bioreactor effluent turbidity value increased from 71.5 to 82.4% as SRT increased from 5 to 15 d. The effluent turbidity value also decreased from 4.2 to 2.6 NTU with an increase in SRT. A higher value of turbidity indicates good sludge-settling properties. The results show that the higher the SRT, the higher the turbidity removal efficiency.

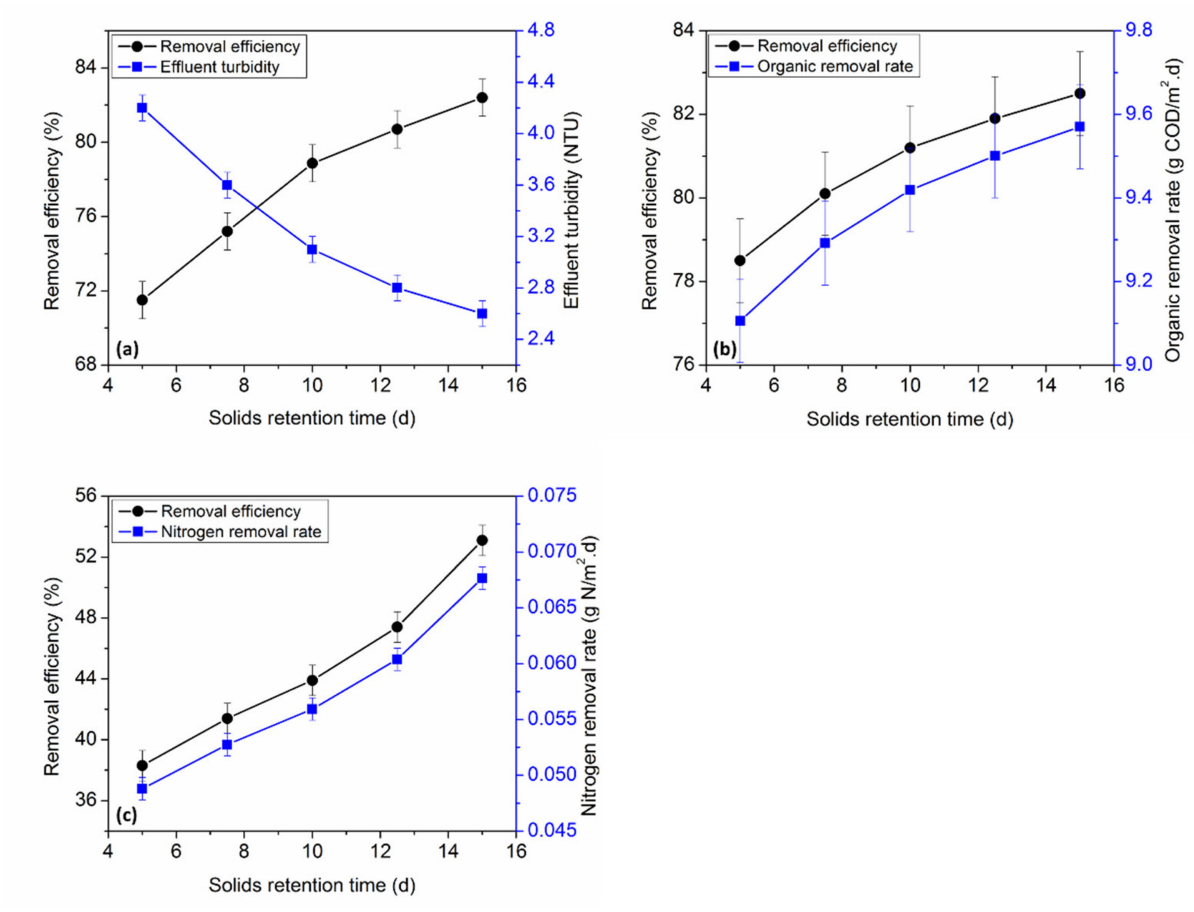

Figure 5. Effect of sludge retention time on (**a**) turbidity, (**b**) COD, and (**c**) TN removal.

Figure 5b shows that excellent treatment efficiency was obtained in COD removal throughout the experiments with little variation with SRT. The COD removal efficiency boosted from 78.5 to 82.5% as SRT increased from 5 to 15 d. This result could be related to the fact that carbonaceous bacteria take 3–5 d to fully acclimatize to the bioreactor. The increase in SRT from 5 to 15 d does not affect the carbonaceous bacterial growth as they are already fully acclimatized. Therefore, the system maintained a high COD removal efficiency and organic removal rate throughout the experiments. Slight changes in COD removal efficiency are due to an increase in sludge age which gives bacteria more time to stay in the bioreactor. The high COD removal efficiency attained in the current study is in good agreement with prior studies on the RBC bioreactor.

The RBC bioreactor showed enhanced nitrification performance throughout the investigation with TN removal efficiency increasing from 38.3 to 53.1% with a rise in SRT from 5 to 15 d as shown in Figure 5c. Meanwhile, the nitrogen removal rate increased from 0.049 to 0.068 g TN/m^2 d. Despite the inherent disadvantage of the absence of anaerobic conditions and low influent TN concentration, the bioreactor showed good nitrification performance. The biofilm growth is significantly affected by the selection of SRT. Higher SRT means microbial biomass is retained in the bioreactor for more time. Nitrogenous bacteria are slow-growing bacteria and take about 14–17 days to fully acclimatize. Higher SRT favors the TN removal as a higher quantity of nitrifying biomass can be retained in the bioreactor and undergo biodegradation. Previous studies highlighted the influence of SRT on microbial activity and enhanced TN removal efficiency along with the higher nitrogen removal rate [35].

3.5. Effect of Hydraulic Rentention Time

Figure 6 describes the influence of HRT on the COD, TN, and turbidity removal. The HRT varied from 6 to 18 h with an equal interval of 3 h at constant 40 rpm disk rotational speed and 15 d SRT. After changing the HRT values, the system was allowed to attain steady-state conditions (48 h). The result indicates that HRT has a significant effect on effluent quality. Figure 5a shows that with the increase in HRT, turbidity removal efficiency increased, and effluent turbidity decreased. The turbidity removal increased from 71.3% to 82.6% as HRT increased from 6 to 18 h. A maximum of 82.6% turbidity removal efficiency with effluent values at 2.62 NTU was achieved at 18 h HRT. The high turbidity removal efficiency at higher HRT results from higher microbial activity and the production of compact sludge that can settle easily.

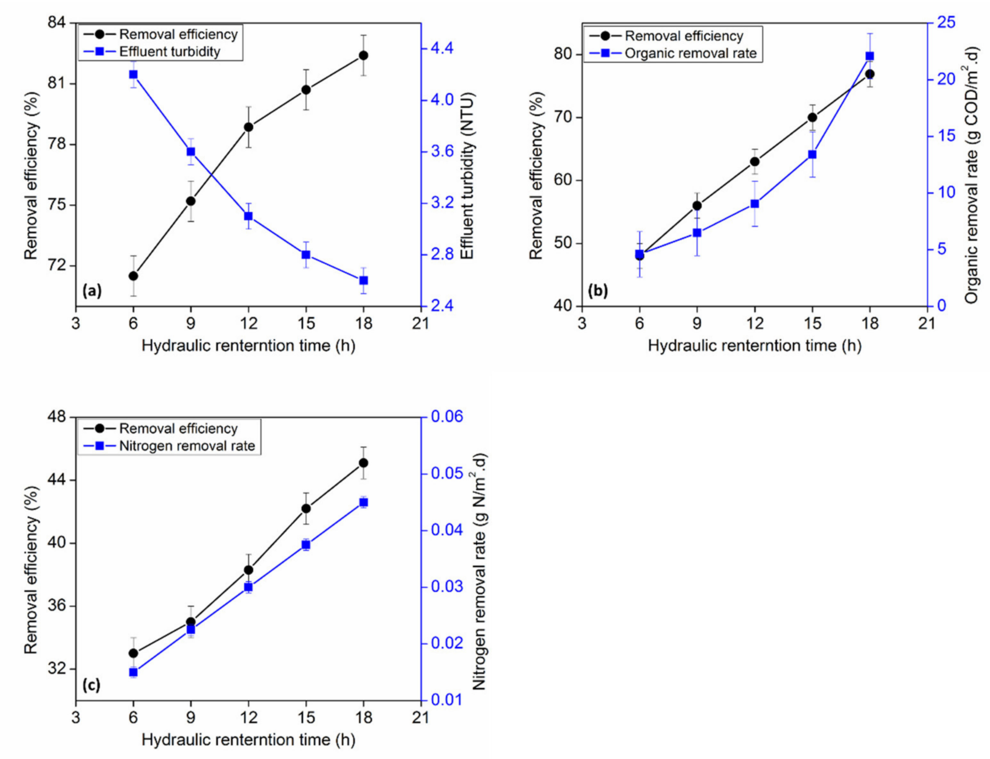

Figure 6. Effect of hydraulic retention time on (**a**) turbidity, (**b**) COD, and (**c**) TN removal.

Figure 6b shows the impact of HRT on the organic removal rate and COD biodegradation in the bioreactor. The COD removal efficiency improved with HRT while the organic removal rate also increased. The COD removal efficiency increased from 48% to 76.9% as HRT increased from 6 to 18 h, and the organic removal rate increases from 4.6 to 22.1 g COD/m^2.d. The organic removal rate improves with HRT until another parameter becomes limiting. The COD removal limitations include insufficient surface area, limited oxygen transfer rate, and hindered carbonaceous bacteria activity.

Figure 6a shows that with the increase in HRT, turbidity removal efficiency increased, and effluent turbidity decreases. Domestic wastewater contains limited TN, which hinders the activity of nitrifying bacteria. The TN removal efficiency and nitrogen removal rate increased with HRT increase. The TN removal increased from 33% to 45.1% as HRT increased from 6 to 18 h. A maximum of 45.1% turbidity removal efficiency with a nitrogen removal rate of 0.084 g N/m^2.d was achieved at 18 h HRT.

3.6. Biomass Characterization

Biofilm systems are rich in microbial biomass containing a variety of microorganisms depending on the operating conditions and influent wastewater. Biofilm acclimatization and the diversity of microorganisms influence the performance of the bioreactor [12]. Physical observation validates the development of a mature biofilm at the carrier medium. At this stage, the microbial biomass can completely undergo the biodegradation process and efficiently undertake the removal of the organics and nutrients.

The biofilm consists of two parts—an aerobic biofilm layer at the outer part of the rotating disk and deep inside the biofilm, anaerobic conditions help the dominance of autotrophic bacteria. Carbonaceous bacteria responsible for carbon removal dominate the biofilm due to the abundance of the substrate in the influent wastewater. The nitrifying bacteria develop slowly and dominate the inner layers of the biofilm. Both the carbonaceous and nitrifying bacteria compete to dominate the biofilm. Domestic wastewater is abundant in carbon sources, which facilitates the growth of carbonaceous bacteria, and the substrate in the influent wastewater comes in contact with the microorganisms [29].

Oxidation of ammonium to nitrate is conducted by AOB under aerobic conditions, while NOB reduce nitrate to nitrogen gas in anaerobic conditions, which only prevail deep inside the biofilm. The abundant carbonaceous bacteria in an RBC biofilm are *Bacteroidetes* and *Proteobacteria*, as indicated by various researchers [22]. The *Bacteroidetes* and *Proteobacteria* dominate the biofilm and form around two-thirds of carbonaceous bacteria. They are abundantly found in the outer layer, where aerobic conditions and the availability of high substrate concentrations are readily available [36].

The influent ammonium concentration and aerobic conditions support AOB proliferation, mainly *Nitrosomonadaceae*, in the biofilm [37]. The *Nitrosomonadaceae* present in the biofilm oxidize the ammonium and convert it to nitrite, which is further oxidized to nitrate. The biofilm analysis suggests that Nitrospira is the main NOB microorganism present in denitrification [38].

3.7. Energy Audit

The energy consumption of the projected RBC was calculated by comparison with a well-optimized full-scale MBR. By adopting the same assumptions and estimation method proposed earlier, the estimated energy consumption optimum conditions in this study was 0.14 kWh/m^3. This value is much lower than the referenced full-scale MBR of 0.64 kWh/m^3. This energy consumption obtained was even lower than the one reported in our earlier study (0.18 kWh/m^3).

The RBC showed a substantially lower energy demand than the referenced bioreactor (Figure 7). The primary energy contributor in the RBC bioreactor is mechanical energy for disk rotation. Disk rotation accounted for only 0.07 kWh/m^3 of energy dissipation compared to coarse-bubble aeration (0.23 kWh/m^3). The overall energy demand of the lab-scale RBC was 0.14 kWh/m^3, which is very low compared to conventional activated-sludge treatment process energy consumption of 0.3–0.4 kWh/m^3. However, the mechanical energy for disk rotation increased exponentially as the number of shafts and the treatment capacity of the bioreactor increased.

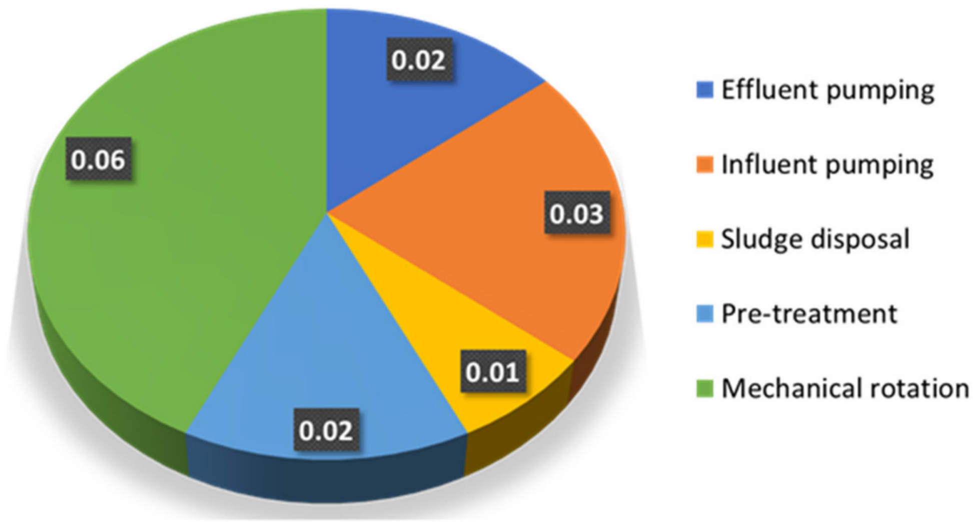

Figure 7. Specific energy demands of the RBC bioreactor.

Submerged MBR adds additional aeration to control membrane fouling, accounting for higher than 50% of energy utilization [39]. Most industrial membrane processes focus on diminishing the total energy requirement by reducing power for membrane aeration while keeping the membrane permeability. A conventional MBR spends around 0.6–0.8 kWh/m^3 of energy; however, it produces less sludge and maintains strict effluent quality [40]. The energy demand in the RBC can be further reduced by employing gravity-driven flow to eliminate the influent and effluent pumping energy demand.

The RBC bioreactor has the capability for energy-efficient treatment of municipal and industrial wastewaters. This outcome is certainly incredibly enthralling and provides the opportunity for considerable improvements to the conventional RBC. The reported energy consumption of the RBC is exceedingly appealing, associated with the CAS for wastewater treatments that utilize the specific energy of 0.3–0.4 kWh/m^3 [40]. An interesting alternative, which may have an additional impact on reducing energy use, will be using new materials, such as polyethylene foam as disc material for rotating biological contactors (RBC). It is important to remember that due to the system's low-energy demand, it is easily operable with renewable energy sources, either solar or wind power [41].

4. Conclusions

The RBC bioreactor achieved superior effluent quality and removal efficiency for domestic wastewater treatment. The average removal efficiency of 73.9% COD, 38.3% TN, 95.6% ammonium, and 78.9% turbidity was attained at a fixed 19 g COD/m^2 d organic loading rate, 9 h HRT, and 30 rpm disk rotational speed. COD, TN, and turbidity removal efficiencies decreased with increased disk rotational, while HRT and SRT positively affected biological performance. At disk rotational speeds higher than 40 rpm, biofilm detachment occurred due to increased shear rate resulting in decreased biological performance and loss of microbial biomass. Higher SRTs increased nitrifying bacteria activity and decreased sludge volumes. The energy audit of the RBC bioreactor shows that it consumed only 0.14 kWh/m^3. Using the disk rotation mechanism to supply oxygen to the microbial activity results in an energy-efficient wastewater treatment process. Therefore, the RBC provides an attractive alternative for treating various types of wastewaters in a decentralized system where issues of a large footprint are less significant.

Author Contributions: M.I., S.R., S.L., I.K., D.G.-K., M.O., S.W. (Sylwia Włodarczak) and K.C.: visualization, analysis, conceptualization, technical editing, re-writing, project management, and resource management; S.W. (Sharjeel Waqas) and J.A.K.: methodology, results, analysis, and manuscript writing. All authors have read and agreed to the published version of the manuscript.

Funding: The APC of the journal was paid by the Opole University of Technology and Poznan University of Technology (from the funds of the Ministry of Education and Science).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors acknowledge the support from the Deanship of Scientific Research, Najran University, Saudi Arabia, for funding this work under the Research Groups funding program grant code number (NU/RG/SERC/11/3). The authors also acknowledge Universiti Teknologi PETRONAS, Malaysia for providing the research facilities.

Conflicts of Interest: The authors declare no conflict of interest.

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