Effect of organic and nitrogen loading rate in a rotating biological contactor for wastewater treatment

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Abstract. A laboratory scale rotating biological contactor (RBC) bioreactor was evaluated for the synthetic municipal wastewater treatment. The decentralized RBC potential advantage of relatively simple design, low HRT and aeration requirement, high loading capacity and relatively high nitrogen removal. An increase in loading rates resulted in enhanced removal rates and decreased removal efficiency for both organics and nitrogen. The bioreactor was operated under loading conditions of 9.6-28.7 g COD/m$^2$.d and 0.085-0.255 g N/m$^2$.d resulted in 48.0-76.9% and 33.0-45% removal efficiency for organics and nitrogen, respectively. The average removal efficiency in terms of chemical oxygen demand, total nitrogen, ammonia and turbidity was 72.4±2.5 mg/L, 38.3±1.9 mg/L, 95.6±0.8 mg/L, and 78.9±0.3 NTU, respectively. Moreover, an energy consumption analysis RBC shows that it consumes significantly less energy compared to other biological processes. Overall results exhibit the effectiveness of the RBC to obtain superior biological performance thus significantly enhances environmental sustainability.

1. Introduction

Biological processes are efficient wastewater treatment techniques maintaining strict environmental regulations whilst economically feasible [1]. In attached growth processes, the microorganisms acclimatize into the packing materials for the conversion of organic materials and nutrients. Rotating biological contactors is an attached growth process possess many advantages such as high specific surface area, high biomass concentration, short hydraulic retention time (HRT), operational simplicity, resistant to shock loadings and low energy consumption [2, 3].

The optimization of RBC design parameters should be based on fundamental data from pilot and full-scale installations. The parameters that affect the bioreactor performance are disk rotational speed, organic and hydraulic loading rate, HRT, disk submergence, recycling, temperature and staging [4]. The disk rotational speed and disk submergence affects oxygen transfer in the biofilm for organics and nutrients biodegradation. Organic and hydraulic loading rate determines the capacity of the treatment plant. RBC is resistant to shock loading conditions thanks to the attached biomass. Due to high treatment capacity and low energy consumption, RBC pose as an efficient for decentralized wastewater treatment applications requiring less maintenance and start-up costs and low land area [5, 6].

RBC has been effectively used by various researchers for domestic and Industrial wastewater. It can undertake chemical oxygen demand (COD) and total nitrogen (TN) removal for domestic and high
strength wastewaters, however, limited enhanced phosphorous recovery has been observed [7]. It has been effective to remove toxic organic compounds such as phenol, toluene and trichloroethylene. Performance of RBC bioreactor has been evaluated for poultry and palm oil mill effluent as high-strength wastewater. Organic materials and nutrients removal have been extensively studied in RBC as an efficient treatment process. For the treatment of high strength organic wastewaters, RBC resulted with efficient removal of organics and nutrients and high performance.

RBC parameters considerably overlap each other, for example the inverse relationship between HRT and OLR. Disk rotational speed and oxygen transfer rate have close relationship with each other. OLR, a key criterion in RBC, defined as substrate (kg organics or nutrients) applied per square meter of media surface area per day. As the OLR increases the pollutants removal rate increases until another parameter becomes limiting. For example, Hiras et al., [5] operated a two stage pre-denitrification and aerobic RBC for treatment of settled municipal sewage under variable OLR. As the OLR increases, the percentage COD removal decreases and COD removal rate increases, respectively. The efficient of substrate utilization decrease with the limiting oxygen transfer rate. [8] operated a three-stage aerobic RBC for treatment of food canning wastewater treatment. A decrease in COD removal efficiency was observed as OLR increased, However, rate of COD removal increased. This can be explained by insufficient disk surface area and limited oxygen mass transfer resulted in insufficient substrate removal efficiency.

RBC have been successfully used for ammonia and TN removal through nitrification and denitrification processes. The nitrifiers dominates the inner layer of biofilm are very stable and form a dominant microorganism layer in the anoxic. Nitrifying bacteria are the major organisms responsible for degradation of ammonia and TN in the domestic and industrial wastewaters.

This study aims to study the RBC bioreactor performance under various hydraulic and organic loading conditions for synthetic domestic wastewater. The RBC performance in terms of COD, ammonium, TN and nitrate were assessed regularly to determine the effect under optimal operating conditions.

2. Materials and Methods

2.1. RBC experimental system

The RBC system made of Plexiglas was fabricated in-house consisted of a storage vessel, bioreactor and settling tank (Figure 1). The bioreactor had a 6.5 L working volume with 25x25x30 cm dimension; five partially submerged media disks, 18 cm in diameter and 1.8 cm thickness connected through a stainless steel. The disks were separated by 3 cm gap to enhance mixing and rotated at 30 rpm perpendicular to the direction of flow. The high rotational speed was selected to prevent solids accumulation and to maintain elevated dissolved oxygen (DO) concentrations. The disks were glued with Polyurethane foam (0.8 cm thickness) on both sides to form biofilm. The influent wastewater was fed from storage vessel through a centrifugal pump and effluent was directed by gravity to the settling tank.

2.2. Wastewater and activated sludge

The synthetic wastewater was prepared by blending food leftover (1 g/L) from the campus canteen (as suggested by [9]). The stock solution was diluted to match the domestic wastewater concentration. The prepared solution was filtered through filter paper (Whatman filter paper, Grade 1 Qualitative Filter Paper Standard Grade) to remove the suspended particles. Basic characteristics of the prepared synthetic wastewater are summarized in Table 1. The characteristics of the feed and effluent were monitored by weekly measuring chemical oxygen demand (COD), total nitrogen (TN), ammonium, pH, total dissolved solids and turbidity during RBC operation. The lab-scale RBC was seeded with activated sludge obtained from full-scale domestic wastewater treatment plant.
2.3. Analytical techniques
All wastewater samples were performed according to Standard Methods [10]. COD, TN, ammonium and nitrate were measured by the Hach method using standard digestion solutions. Each specific vial was inserted into Hach DR3900 lab-scale spectrophotometer for reading. pH and turbidity were measured using Hach 2100Q portable turbidimeter and Hach HQ411D benchtop PH/MV meter, respectively.

2.4. RBC start-up
The RBC start-up involved continuous supply of influent wastewater RBC to fully acclimatize the biofilm. Bioreactor was inoculated with synthetic wastewater at constant hydraulic loading rate (HLR) of 12 ml/min to give a 9 h HRT and organic loading rate (OLR) of 17 g COD/m².d for 15 d. 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. At the end of 15 d period, biofilm completely acclimatized at the disk surface and the bioreactor performance under various operating conditions was stated.

2.5. RBC operation
After the acclimatization stage, the analysis of wastewater was conducted every three days to analyze the effluent quality. The bioreactor was operated for a period of 45 days to determine the effect of biological performance on various operational parameters. No sludge was removed from the bioreactor during this period; hence sludge retention time was unlimited.

3. Results and Discussion
3.1. Biological performance
Figure 2 shows the variations of COD, TN, ammonium and turbidity for the RBC influent and effluent over the experimentation period. During the 1-30 d period, RBC maintains a high COD removal efficiency, while during 31-45 d period, removal efficiency deteriorated as a result of biofilm detachment. This conclusion is supported by the corresponding effluent turbidity values. Turbidity values were lower during 1-30 d period maintaining a low effluent value which deteriorates during the biofilm detachment period. The old mature biofilm layer shreds from rotating disks and suspends into wastewater.

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). RBC develops abundant AOB and NOB throughout the biofilm along with carbonaceous bacteria. Nitrification occurred in RBC without encountering any problem as biofilm
have low biomass yield and very high sludge ages. The RBC exhibits excellent ammonium removal efficiency throughout the experimentation period and achieves a highest removal efficiency of 95.6±0.8% with 0.03 mg/L effluent values. Wastewater with high organics concentration, heterotrophic bacteria significantly diminishes nitrifiers growth. Therefore, nitrogen removal occurs after organics removal during the last stage of the RBC bioreactor [11].

Figure 2. Variation of COD, ammonia, TN and turbidity throughout the experimentation period.

The average effluent COD was 78.2±7.5 mg/L with 72.4±2.5% average removal efficiency whereas, the average effluent TN was 1.54±0.05 mg/L with 38.3±1.9% average removal efficiency. The RBC obtained the higher COD removal efficiency in the first 30 d with average COD effluent was 73.4±3.0mg/L with average removal at 73.3±1.1%. The biofilm detachment results in increased effluent turbidity values, which increases from 3.1 NTU to 3.8 NTU. On the other hand, TN removal efficiency increases as suspended flocs also contributes to the biodegradation. The COD reduction and turbidity rise confirms the effluent quality deterioration. It can be concluded from that the removal efficiency of COD and turbidity for the RBC are high enough to satisfy the treatment requirements.

Some reports have reported that RBC has the capacity of aerobic denitrification. Lower DO concentration at the bottom of RBC, it facilitates denitrification [12]. 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.

3.2. Effect of loading rate on RBC performance

Figure 3 shows relationship of COD removal rate and COD removal efficiency at various OLR at steady state conditions. RBC performance was assessed at various OLR by varying HRT from 18 to 6 h subsequently decreased at an equal interval of 3 h and constant influent COD of 282±8.2 mg/L. The bioreactor was started with 18 h HRT equivalent to OLR of 9.6 g COD/m².d. There is inverse relationship between HRT and OLR, hence HRT was decreased to achieve an OLR of 28.7 g COD/m².d at constant influent COD (282±8.2 mg/L). As OLR increased from 9.6 to 28.7 g COD/m².d, COD removal efficiency decreased from 76.9 to 48.0%. On the other hand, COD removal rate increased from 7.4 to 13.8 g COD/m².d. Limitation of oxygen transfer rate and insufficient surface
area are the limiting factors for reduction of COD removal efficiency. Maximum COD removal efficiency (76.9%) was obtained at 18 h HRT. [8] evaluated the performance of a three stage RBC bioreactor for the treatment food canning wastewater and results depicted that as HRT increased from 24 to 48 h, COD removal efficiency increased from 85.3 to 97.4%. In RBC, as the OLR increases, the removal rate increases until another parameter becomes limiting. [5] operated a two-stage aerobic RBC for the settled municipal sewage treatment. As OLR increases (90 to 360 g/m². d), COD removal efficiency decreases from 50% to 35%. Increased removal rate suggested more capacity for bulk COD removal, therefore, maximum removal rate was achieved at the highest loading conditions [13].

![Figure 3. Effect of organic loading rate on organic removal.](image1)

![Figure 4. Effect of nitrogen loading rate on nitrogen removal.](image2)

RBC bioreactor successfully achieved TN removal although TN concentration of domestic wastewater was very low. Figure 4 shows TN removal efficiency and removal rate against nitrogen
loading rate. The nitrogen loading rate has the same inverse relationship with HRT as COD. The bioreactor was started with 18 h HRT equivalent to nitrogen loading rate of 0.085 g N/m².d. HRT was decreased from 18 to 6 h to achieve an nitrogen loading rate of 0.255 g N/m².d at constant influent TN (2.5±0.02 mg/L). As nitrogen loading rate increased from 0.085 to 0.255 g N/m².d, nitrogen removal efficiency decreased from 45.1 to 33.0%. On the other hand, nitrogen removal rate increased from 0.038 to 0.084 g N/m².d. The maximum nitrogen removal efficiency was 45.1% at 18 h HRT and it decreased slightly as nitrogen loading rate increased. This is attributed to insufficient influent TN concentration availability for the nitrifying bacteria to acclimatize hence limits the removal capacity. [14] operated an RBC for treatment of municipal landfill leachate under various ammonia loading condition. As ammonia loading increase from 1.92 to 4.79 g/m².d, nitrification efficiency decreases significantly. This concludes that as nitrogen loading rate increases, nitrogen removal rate also increases with decrease in overall removal efficiency.

3.3. Effect of loading rate on RBC performance
Figure 5 demonstrates the effect of effluent turbidity at various HRT. The turbidity decreased with the increased in HRT and reached a minimum of 2.6 NTU at 18 h HRT. As HRT increased from 6 to 18 h, effluent turbidity decreased from 4.2 to 2.6 NTU and removal efficiency increased from 71.5% to 82.4%. RBC’s mixed liquor vapor suspended solids are three times higher the CAS requiring no sludge recycling and lower energy requirement. The effluent pH remained in the range of 6.84-7.02 throughout the experimentation. No significant change in the effluent pH was observed signifies the microorganism’s acclimatization and enough media surface area for substrate degradation.

![Figure 5. Effect of hydraulic retention time on effluent turbidity.](image)

3.4. Biomass characteristics
The thickness of biofilm varies and does not always cover the entire disk surface in the aerobic RBC bioreactor. The aged biofilm detached from the disk surface at higher disk rotations. This detached biofilm does not easily settle down and remain suspended in the bioreactor. Due to specific nature of RBC bioreactor, these suspended flocs grow in suspension. Therefore, suspended flocs along with the attached microorganisms take part in the organics and nitrogen removal. The detached biofilm remains suspended in the bioreactor and have better access to DO and biodegradable pollutants. The growth of suspended flocs is called seeding effect and rich with nitrifiers significantly improving TN removal. Higher disk rotational speeds leads to severe detachment results in was-out of the attached biofilm and adversely affect the pollutants biodegradation [15].
3.5. Energy efficient RBC

Stringent regulations and increased demand govern organic and nitrogen discharge, rising energy cost and greenhouse gas emission are a growing concern for the development of an efficient green energy wastewater treatment plant. The decentralized RBC potential advantage of relatively simple design, low HRT and aeration requirement, high loading capacity and relatively high nitrogen removal provide a platform for energy generating processes. The absence of coarse bubble aeration, a major energy factor for CAS process, is a significant advantage in RBC reducing the overall operating cost. In RBC, Media disk rotation and percentage submergence leads to convective air/water exchange. Increased rotational speed increases the total oxygen transfer rate however, energy factor rises exponentially with increasing disk rotation. An optimized disk rotational speed for optimum oxygen transfer rate can significantly enhance the overall efficiency of the process.

A hybrid RBC system has been applied for energy or electricity production through algae and biogas [16, 17]. An algae-RBC bioreactor proved successful for nitrogen and phosphorous removal and indirect energy generation [18]. The RBC is therefore an ideal candidate for hybrid processes for upgrading works maximizing efficiency of existing infrastructure and minimizing energy consumption for nutrient removal. Higher rate of denitrification was observed in a RBC where electron generation at anode was utilized for nitrate reduction at cathode [16]. It should be emphasized that the biological performance for wastewater treatment by other techniques like moving bed biofilm reactor and MBR virtually is higher than the RBC. However, RBC presents as a promising method for reuse purposes considering low operational and maintenance cost, and operational ease.

4. Conclusions

The RBC bioreactor was obtained superior biological performance in domestic wastewater treatment. A maximum removal efficiency of 72.4±2.5% COD, 38.3±1.9% TN, 95.6±0.8 ammonia, and 78.9±0.3% turbidity removal was achieved at HRT of 12 h. The COD and TN removal efficiency decreased with an increase in loading rate and maximum removal efficiency of 76.9% and 45% were obtained, respectively. The organic and nitrogen removal rate increased with loading rate and resulted in highest value of 13.8 g COD/m².d and 0.084 g N/m².d, respectively. The RBC was concluded as an effective process for domestic wastewater treatment under high loading conditions with momentous effluent qualities. The simplicity, adaptability, low land use and maintenance and high volumetric activity of the RBC suggest that it will continue to help meet our wastewater treatment requirements for years to come.

Acknowledgment

Authors acknowledge the funding support of the Ministry of Science, Technology and Innovation, Government of Malaysia through Fundamental Research Grant (No. 015MA0-039) and Universiti Teknologi PETRONAS for providing the research facilities.

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