



A Review on Rotating Biological Contactors

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ABSTRACTS

Rotating biological contactors (RBC) is a wastewater treatment process that provides a both acceptable effluent quality and organic removal efficiency at a comparatively very low costs. It is highly attractive due to simplicity of operation, low sludge production, small foot-print, low maintenance, and low operational cost. Complete nitrification/denitrification can be achieved by varying the disk submergence level and operating the process under both anaerobic/anoxic conditions in a single unit. In this review, pros and cons of RBC are discussed in detail along with the factors affecting its performances. Organic and hydraulic loading and hydraulic retention time are the main parameters followed by additional parameters such as rotational speed, media, disk submergence, dissolved oxygen level, influent and effluent characteristics, and step-feeding in affecting the performance of an RBC system. RBC has shown promising results for the removal of biodegradable matter, nitrogen and phosphorous removal. The approaches for hybridization of biological processes to improve their overall performance are also review. Such success story is assess so explore possibility of developing RBC based hybrid processes. Hybrid RBC can be form from in-combination with other processes for minimizing energy requirements and maximizing the efficiency of the system.

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1. INTRODUCTION

Wastewater treatment processes ought to follow standards that help to ensure environmental sustainability (Pebriyanti *et al.*, 2016). A variety of physical, chemical, and biological processes are used for wastewater treatment. All of them have their own merits and limitations (Rajasulochana and Preethy, 2016). For example, high effluent quality is achieved by traditional biological processes in expenses of high energy usage largely for reactor aeration. It accounts for about 55% of the total energy budget for wastewater treatment. Development of a wastewater treatment technology can further improve effluent quality and increase pollutants removal efficiency (Hoyland *et al.*, 2010).

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 (Lee *et al.*, 2001). Biological treatment processes include attached growth and suspended growth processes. For the former, microorganisms are attached to a solid surface, while for the latter, the microorganisms are in suspension. Trickling filters and rotating biological contactor (RBC) are attached growth processes while activated sludge (AS) process and membrane bioreactor (MBR) are the suspended growth processes. These biological treatment methods are employed worldwide to treat domestic and industrial wastewater (Wiszniewski *et al.*, 2006).

RBC is the attached growth process in which microorganisms are attached to a media by developing a film. RBC constitutes a precise distinctive and superior substitute process for biodegradable matter as well as nitrogen removal. Some of the potential advantages of RBC as compared to conventional AS and trickling filter process are as follows: low land requirement, simple process control and monitoring, little

operational and maintenance costs, high biomass concentration, low excess sludge production, short hydraulic retention time, high oxygen transfer efficiency, no need of sludge recirculation, process is resistant to shock and toxic loads and compact design (Cortez *et al.*, 2008; Patwardhan, 2003; Rodgers and Zhan, 2003).

2. ROTATING BIOLOGICAL CONTACTORS

The RBC was first originated in Germany in 1920s and was first described as a “rotating aerobic mass” fixed to a media support (Chan and Stenstrom, 1981). The first plant was registered in the United States and was named the “contact filter” or “biological wheel” (Doman, 1929). Commercial importance in RBC was nominal, until the development of drip body immersion system. This leads to the development of first experimental pilot scale RBC. This milestone study opened new ways for future RBC design which evolved in the 1960s (Hassard *et al.*, 2015). Historically, RBC have been used for the treatment of wastewater for organic carbon removal. The use of this process was later expanded to include nitrification and denitrification of wastewater. Early RBC systems began in Europe and have been in continuous operation since 1958 (Poon *et al.*, 1979). A schematic diagram of RBC is shown in **Figure 1**.

2.1. Types

RBC consists of two main types; integral and modular. Integral systems consist of a single unit combining all three steps i.e., primary settlement, RBC biological zone and final clarifier. Integral systems have a treatment capacity of ≤ 250 population equivalents (PE) (Findlay, 1993). Modular systems, on the other hand, consists of separate units for primary treatment, RBC biological process and solids treatment and have a treatment capacity of PE >1000 . The treatment capacity allows more flexible configurations (Griffin and Findlay, 2000). Parallel flow arrangement of RBC can be

operated for acceptable loading limits. But if the effluent quality is a matter of concern, RBC is placed in series. 40% submergence of the disc is usually used (Cortez *et al.*, 2008). If submergence is increased, less oxygen is supplied to the microorganism and conditions in the reactor becomes anaerobic and the process becomes favorable for denitrification (Teixeira and Oliveira, 2001).

RBC is a wastewater treatment process that provides a both acceptable effluent quality and organic removal efficiency at a comparatively very low costs. It is highly attractive due to simplicity of operation, low sludge production, small foot-print, low maintenance and low operational cost. Complete nitrification/denitrification can be achieved by varying the disk submergence level and operating the process under both anaerobic/anoxic conditions in a single unit. In this review, pros and cons of RBC are discussed in detail along with the factors affecting its performances. Organic and hydraulic loading and hydraulic retention time are the main parameters followed by additional parameters such as rotational speed, media, disk submergence, dissolved oxygen level, influent and effluent characteristics, and step-feeding in affecting the performance of an RBC system. RBC has shown promising results for the removal of biodegradable matter, nitrogen and phosphorous removal. The approaches for hybridization of biological processes to improve their overall performance are also review. Such success story is assess so explore possibility of developing RBC based hybrid processes. Hybrid RBC can be form from in-combination with other processes for minimizing energy requirements and maximizing the efficiency of the system.

2.2. Advantages

RBC is preferable for wastewater treatment because of its simplicity, low operating and maintenance costs and

reliable performance (Cortez *et al.*, 2008). A variety of process parameters for RBC has been discussed in the literature. The operational expenditure and maintenance cost of the RBC is less than the AS process. In AS process, aeration cost is much higher which increases the operational cost of the overall process. In RBC, no aeration is required due to the direct contact of media with the air through rotation of the disks. The capital expenditure for RBC is inversely proportional to the particulate equivalents. The capital cost for RBC is less than the AS process because of the less requirement of material. The energy usage is about half of the AS process because of no need of aeration (Hassard *et al.*, 2015).

RBC process is resistant to the toxic and shock loads making it a more reliable process to be used for wastewater treatment. The microorganisms in the RBC are attached to the media and biodegradation occurs at the media surface. With the rise in organic loading, the microorganisms do not wash out, making the process more feasible to handle organic shock loads. The same is the case for the increase in toxic loads, more food is available to the microorganism. AS process has microorganisms in the suspended form so any rise in load will wash out the suspended microorganisms and results in poor treatment. An increase in hydraulic and organic loading will wash out the microorganisms (Kapoor *et al.*, 2003). The prime advantage of attached growth processes is the handling of higher organic loadings due to uncoupling of mean cell residence time (MCRT) from HRT (Hassard *et al.*, 2015).

RBC produces fewer and more concentrated sludge as compared to AS process. Due to this, a smaller secondary clarifier is required for the settling of the sludge. The size of the floc is larger in RBC due to the attached biodegrading of the organic matter as compared to the suspended

growth process. The volume of sludge is less in RBC due to the longer solids/sludge retention time. It is evident from the literature that sludge volume is about 10% to 20% less than conventional AS process.

Only relatively short hydraulic retention time (HRT) is required because of the large active surface area. High biomass concentrations are available for degradation, which reduces the sludge production and the system does not require sludge recirculation. High oxygen transfer efficiency eliminates the need of aeration to transfer the oxygen from gas to liquid phase which makes the process to run at low operational cost (Hassard *et al.*, 2015). Land requirement is low for RBC as compared to AS process. RBC consumes about a half of energy consumption in AS process.

One greatest advantage of RBC is ease of operation. RBC operates with slight monitoring and maintenance cost is low (Cortez *et al.*, 2008). In AS process, a portion of the settled sludge is returned from the secondary clarifier back to the aeration tank to meet the required amount of microorganisms in the bioreactor. But in RBC, thanks to the excess of microorganisms, no recirculation is required. From all of those advantages, RBC seems to be highly attractive for treating certain treatment plants for their established simplicity, low energy usage, and consistent performance.

RBC process is very easy to monitor and operate. Low maintenance cost of the process makes the process more feasible for large-scale applications. RBC is resistant to shock loads, which makes the process economics more profitable.

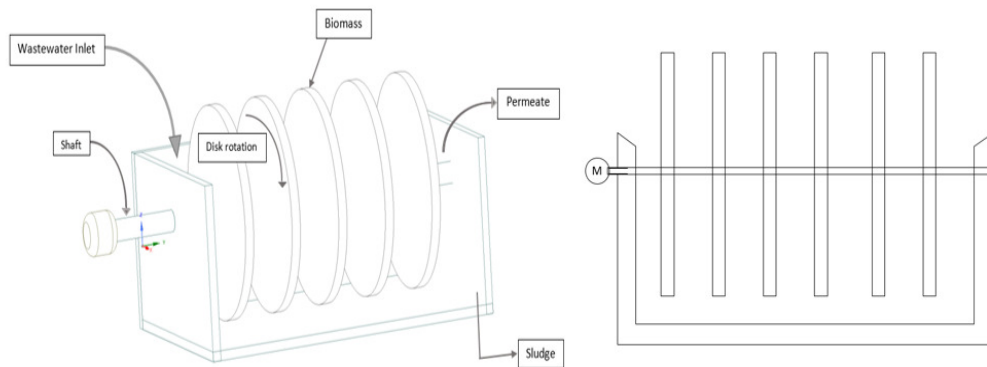


Figure 1. Schematic diagram of conventional RBC unit.

3. FACTORS AFFECTING RBC PERFORMANCES

RBC performance depends upon numerous design parameters. The most basic parameter to affect the performance is HRT, and organic and hydraulic loading rates. It was thought in the past that these parameters only govern the performance of the treatment plant. A detailed study on the process evolved that a variety of factors contribute in the overall performance and the relationship between these parameters establish the overall behavior of the

treatment process. The main parameters of importance are rotational speed, HRT, hydraulic loading rate (HLR), organic loading rate (OLR), disk media, wastewater characteristics, temperature, types of microorganisms, dissolved oxygen (DO), media submergence, step-feeding, and sludge recirculation.

3.1. Rotational speed

Rotational speed is directly related to the DO levels in the wastewater. As the rotational speed increases, the DO level also increases. This is due the fact that with the

rise in rotational speed, the contact of microorganisms with the air increases resulting in the increased level of oxygen. This increases the degradation of substrate and results in the increased performance of the bioreactor rate (Israni *et al.*, 2002). However, more power is consumed with the increase in rotational speed which can affect the economics of the treatment process. With the rise in rotational speed, microorganisms can detach from the media surface and deteriorate the effluent which results in poor treatment. Low rotational speed results in reduced DO in the bioreactor slowing the degradation process (Ramsay *et al.*, 2006).

Due to the larger surface area, packed supports provide more oxygenation as compared to disk media for the same value of rotational speed but energy consumption will be more due to the large surface area. An optimum value of rotational speed must be chosen in order to get the proper effluent quality and economics of the process.

3.2. Organic loading rate

The organic loading rate was thought to be one of the main parameter controlling the treatment process. OLR is varied by fluctuating the inlet flow rate or the HRT, which also changes the HLR (Najafpour *et al.*, 2005). With the increase in OLR, the removal efficiency decreases but substrate removal rate increases. This reduction in removal efficiency is due to the limitation of DO. More loading increases the process of degradation, increasing the need of DO in the bioreactor. The depletion of DO gradually slows the process of degradation and results in inadequate treatment.

In the first stage of RBC, carbonaceous substances are mainly removed resulting in depletion of DO. To avoid the problem of limited oxygen levels, first stage OLR must be controlled and set according to the capacity

of the system. High loading could result in problems like sub-standard treatment, DO depletion, excessive biofilm thickness, odor problems, decline in process performance, and growth of unwanted microorganism, *Beggiatoa sp.*

3.3. Hydraulic loading rate

Historically, RBC performance has been correlated with HLR. HLR plays an important role in defining the performance of the bioreactor. Increasing the flow rate of the influent, reduces the retention time of wastewater which results in poor treatment efficiency. In a well-defined system, increase in HLR leads to an increase of microorganisms in the bioreactor (Alemzadeh and Vossoughi, 2001). Hydraulic loading is coupled with effluent quality, substrate, and the design of the RBC. RBC developers plot the hydraulic loading against effluent quality to depict the importance of parameter. These graphs can be useful in characterizing the full-scale system and for the up-gradation of lab-scale systems. The presence of large amount of microorganisms in the bioreactor offers excellent stability under toxic and high loadings (Sirianuntapiboon, 2006).

3.4. Hydraulic retention time

HRT is directly related with the organic and hydraulic loading of the influent wastewater. Longer HRT facilitates proper degradation of the substrate substances and improved removal efficiencies (Hanhan *et al.*, 2005; Najafpour *et al.*, 2006). The trend remains the same for toxic and heavy metal substrates (Costley and Wallis, 2000; Majumder and Gupta, 2007; Sirianuntapiboon and Chuamkaew, 2007). Short HRT will result in poor treatment process due to improper degradation of the substrate while longer HRT will affect the economics of the process. The selection of the optimized HRT is very important in

obtaining the desired effluent quality at the minimal cost (Costley and Wallis, 2000).

3.5. Media

RBC media is one of the main parameter that affects the performance of the system. Different types of media are in use to stretch extra surface area per unit volume. The more the area per unit volume of the media, more microorganisms can grow and this increase the removal efficiency. However, the cost of the media should be considered while selecting one (Ware *et al.*, 1990).

RBC media is produced from high-density polyethylene (HDPE), Styrofoam, polycarbonate sheets, and others. HDPE is most commonly used material as media and is fabricated in different shapes and configurations according to the requirement of the process (Rodgers and Zhan, 2003; Ware *et al.*, 1990). The configuration offers the advantage of improved mass transfer, enhanced structural stability and increased surface area.

3.6. Staging

RBC media is designed in different stages to maximize the removal of BOD₅ and nitrogen substances. Staging can be accomplished by introducing baffles in the tank or by using a series of tanks. For the secondary treatment applications, minimum number of three stages are recommended for the proper treatment. Nitrification/denitrification and BOD₅ combine required atleast four stages per flow. Small plants can be run by connecting all stages to a single shaft which is parallel to the flow direction. In large installments, one or more shaft are mounted perpendicular to the flow direction employing several stages in series. The system is designed in a manner that as the wastewater flows through the bioreactor, each stage entertains an influent with an organic loading lower than the preceding stage. The first stage removes organics because of the faster growth of

heterotrophic bacteria rather than nitritiers. The removal of ammonia and other nitrogen compounds occur in the last stages of the bioreactor to produce nitrates as final product.

3.7. Wastewater characteristics

The influent wastewater concentration and presence of different substances is very important considering the operation of bioreactor. The flow stream with large amount of substrates may take longer retention times and the flux may be smaller. Presence of particulate matter tends to reduce the flux into the biofilm because they occupies space and hence decreases the rate of degradation. The presence of sulphide in the wastewater or its growth into the biofilm will favour the development of sulphide-oxidizing bacteria which cause oxygen depletion in the system decreasing the performance. *Beggiatoa sp.* is one type of sulphide-oxidizing bacteria that competes with heterotrophic bacteria for oxygen and hence shifting the process from organics removal to nitrites removal. In extreme cases, *Beggiatoa* will take over the first stage, shifting the organics to the next stage and subsequently taking over the whole process (Mba *et al.*, 1999).

3.8. Dissolved oxygen levels

In RBC, the rotation of the disk allows the biofilm to come in-contact with the air. The exposure of biofilm to the air can be controlled by submergence of the disks in the wastewater. The continuous rotation of the disk exposes the biofilm to wastewater and atmospheric oxygen. The transfer of oxygen occurs in three ways: (i) by direct contact of air and water at the air-water interface, (ii) oxygen adsorption by the liquid film attached to the media surface when it is in air, and (iii) by microorganisms when they are exposed to air.

In the initial stages of the bioreactor, DO concentrations touches minimal levels,

which tends to increase during the last stages when substrate concentrations are low. Usually, an increase in rotational speed results in increased DO levels. Oxygen transfer capacity is also increased with increase in rotational speed (Rodgers and Zhan, 2003). In an aerobic reactor; During the carbonaceous oxidation step and nitrification process; DO levels play an important role in defining the performance. A supplementary oxygen source can be installed to account for the required amount of oxygen for degradation process (Rodgers and Zhan, 2003; Surampalli and Baumann, 1997).

3.9. Step-feeding

In order to avoid depleted levels of DO in the bioreactor, influent wastewater is step-fed into the system. This process of step-feeding not only accomplishes adequate DO levels in the wastewater and increases the process capacity. Shock loadings can be avoided by this method and to have a more robust performance of the bioreactor (Janczukowicz and Klimiuk, 1992; Saikaly and Ayoub, 2003).

4. DRAWBACKS

RBC has a few drawbacks which include: slow process start-up, requiring adequate primary pre-treatment, requiring secondary clarifier, limited process flexibility and difficult to scale-up. In comparison to MBR, RBC offers lower effluent quality and lower removal efficiency.

In RBC, a specific thickness of biofilm is necessary to start the process and to sufficiently digest the organic matter in wastewater. This layer of microorganisms develops with time and delays the process start-up (approximately 3-6 months). Adequate primary pre-treatment is also essential to remove the large solid particles. Digestion of organic matter follows at the attached media and extra sludge is produced at the surface of the media. This extra sludge

produced hinders the way of oxygen transfer and reduces the efficiency of the process. Detachment of this layer from the media is done by shear forces. Settling of the detached sludge is necessary to achieve the desired effluent quality of water. A secondary clarifier is attached to the RBC to settle the sludge produced and to achieve the desired effluent quality.

RBC has limited process flexibility, as it restricts the removal of multiple materials with the same microorganisms. Industrial and municipal wastewater contains various types of organic matter, nutrients, carbohydrates, proteins, and fats. A wide range of microorganisms is required to degrade these all types of wastewater to ensure the better effluent quality. Microorganisms digest the type of food that is favorable for them (Peavy *et al.*, 1985). The choice of the microorganisms is specific to the characteristics of the influent wastewater. A variety of microorganisms are available for the removal of a wide range of materials but selection of best microorganisms to digest the food is very important parameter. In this regard, a number of parameters incorporate in the scale-up of RBC such as hydrodynamics, hydraulic flow, organic loading, oxygen transfer, active media surface area, microorganism growth and detachment from the biofilm. The developed models only consider one of the parameter and does not include the relationship between different parameters governing the process. Dutta *et al.* (2007) fabricated three different RBC to distinguish the oxygen transfer coefficient at different levels. But, while considering the scale up of bio reactor, the oxygen transfer should be appropriately characterized. Empirical design parameters have been developed. But, they do not exactly address the same process conditions as in the lab-scale.

5. RBC VERSUS OTHER WASTEWATER TREATMENT SYSTEMS

RBC provides adequate treatment quality when operated according to the requirement. It provides better effluent quality and excellent controls as compared to AS process. A comparison of different parameters for RBC, activated sludge (AS) process, and membrane bioreactor (MBR) is given in **Table 1**. RBC and AS process both produce high quality effluents but RBC can handle toxic and shock hydraulic and organic loadings in treating wastewater. The overall removal efficiency is about 99% for organic removal and 90% for nitrogen removal in RBC. The production of sludge is low because of the attached and excess growth of microorganisms. The operating cost of RBC is low; which makes the process cost effective; because of no need of aeration.

6. OTHER BIOLOGICAL TREATMENT SYSTEMS

A hybrid system usually consists of two or more sources or methods used together. In terms of wastewater hybrid systems, there are various types of possible combination methods used for wastewater treatment. Hybrid systems are common to achieve the desired quality of the effluent wastewater at minimum cost.

These include moving bed biofilm reactor (MBBR), integrated fixed-film activated sludge (IFAS), fluidized bed bioreactor (FBBR) and membrane bioreactor (MBR). Hybrid activated sludge/MBBR process have been investigated for treatment of municipal wastewater in cold climates (*Di Trapani et al., 2011*). In MBBR process, small cylinder-shaped polyethylene media elements are placed in the aeration tank to support biofilm support. A perforated plate is installed at the outlet of the tank to prevent the discharge of media with the effluent. The media acts as carrier to the biofilm and is distributed evenly throughout the aerated tank. Advantages of the MBBR

process include: no backwash requirement, no clogging, sludge recirculation is not required, and high specific biofilm surface (*Andreottola et al., 2003; Ødegaard et al., 1994*).

In the IFAS process, a fixed packing material is placed in an activated sludge reactor. The packing can be in the form of frames, foam pads, etc. suspended in the aeration tank. The process is different from MBBR as it uses return sludge flow. The purpose of fixed film medium is to increase the microorganism concentration in the bioreactor. This increases the capacity of the bioreactor without increasing the reactor volume (*Randall and Sen, 1996*).

In the FBBR, wastewater enters from the bottom of the aeration tank and flows upward through a bed of sand or activated carbon. Activated carbon is usually used since it can be prepared from various organic materials (*Anshar et al., 2016; Nandiyanto et al., 2017; Nandiyanto et al., 2018*), provides both adsorption properties and media surface for the growth of microorganisms. Effluent recirculation is performed to provide the fluid velocity with the necessary detention times. FBBR offer advantages of long SRT, ability to handle shock loads, produces high quality effluent, and operation is simple and reliable. Forward osmosis (FO) is another membrane process that can separate a concentrated and diluted solution. The permeability of water is due to the osmotic pressure applied across the membrane (*Bilad, 2016*).

The purpose of forming a hybrid process is to diminish the disadvantages of both the process and to increase the quality of effluent water. RBC is combined with another unit operation to improve the stability of the process against variable loading and improve the effluent standard. Most common configurations of hybrid systems in practice include a RBC/biofilm system. RBC/biofilm system has been applied to improve discharge quality and provide a flow buffer for shock loading. Combining RBC/AS is also common practice.

Table 1. Comparison of different biological treatment processes.

Parameter	Activated Sludge	RBC	MBR
Ease of Operation	Simple operation but required continuous monitoring (Gupta and Bhardwaj, 2016).	Simple operation requiring less maintenance and monitoring. No complex process parameter is involved.	Simple operation but requires continuous monitoring and maintenance to avoid membrane fouling.
Aeration Requirement	Oxygen supplied by mechanical or diffused air aeration.	Oxygen is supplied by contact of rotating contactor with air.	Oxygen supplied by either mechanical or diffused air aeration.
TN and TP	Can remove N and related compounds by nitrification and denitrification.	The overall removal efficiency was approximately 99% for organics removal and 90% for nitrogen removal (Trikoilidou <i>et al.</i> , 2016). Complete nitrification and denitrification is achievable in anaerobic RBC.	On average, the removal efficiency for TN and TP was 83% and 55% respectively, with 8-15 h HRT and a very long SRT (Yeom <i>et al.</i> , 1999).
Sludge production	High production of sludge	Low sludge production due to high biomass concentration (Safa <i>et al.</i> , 2014).	Endogenous respiration of a microbial community in MBR can be encouraged by very high sludge age, i.e., high sludge concentration. Low sludge volume index as compared to AS process due to the retention of sludge at the surface of the membrane.
Energy Requirement	High energy consumption	Low energy consumption because no aeration is required in the bioreactor (Hassard <i>et al.</i> , 2015).	Adequate energy requirement. Energy associated with aeration accounts to about 50% of the total energy input.
Solids Retention Time	High solids retention time	High solids retention time decreases the amount of sludge and large floc size facilitates the settling process.	High solids retention time facilitates the amount of microorganisms in the bioreactor. The average sludge retention time is 30 days (Grelier <i>et al.</i> , 2006).
Hydraulic Retention Time	High HRT compared to RBC	Short HRT of about 4 h was used for the removal of organic matter. This is because of the large amount of microorganisms available for digestion of organic matter (Kapoor <i>et al.</i> , 2003).	HRT=8 h and T=25 °C are the preferred operating conditions, resulting in high flow rate and low membrane fouling (Hemmati <i>et al.</i> , 2012).
Land Required	Large area is required	About 1/10 th land is required as compared to AS process (Cortez <i>et al.</i> , 2008).	Due to the low volume of sludge, land requirement is minimum as compared to AS process.

Table 1 (continue). Comparison of different biological treatment processes.

Parameter	Activated Sludge	RBC	MBR
Organic Loading Rate	Sensitive to OLR due to less amount of microorganisms present.	OLR of 24g COD/m ² /day was used (Al-Ahmady, 2005).	OLR ranging from 5 to 12 kg COD/m ³ d ¹ (Wijekoon <i>et al.</i> , 2011).
Aeration Cost	About 55% of the OPEX	No aeration is required due to the rotation of the shaft.	At low MLSS, aeration cost is low which tend to increase with the rise in MLSS. Aeration cost account to about 50% of the operational expenditure in MBR because excessive aeration is required (Yoon <i>et al.</i> , 2004).
COPEX and OPEX	High COPEX and OPEX	An RBC was found to be on average 35% cheaper per year compared to trickling filters due to lower land area and running costs (Hassard <i>et al.</i> , 2015).	COPEX is equal to the RBC process but OPEX is high because of aeration and membrane fouling.
Primary Treatment Requirement	Adequate primary treatment is required.	Adequate primary treatment is required.	Adequate primary treatment is required in order to reduce membrane fouling.
Secondary Clarifier Requirement	Secondary clarifier is required for the settling of sludge.	Integral RBC does not require secondary clarifier (Hassard <i>et al.</i> , 2015).	No need for secondary clarifier because membrane will retain the organic matter, microorganisms and waste materials.
Scale-Up	Easy to scale-up. Adopted for any size of community.	RBC is difficult to scale-up (Hassard <i>et al.</i> , 2015).	Scale-up is easy but should account for the COPEX and OPEX.
Sludge volume index	High sludge volume index values in the secondary clarifier.	Low sludge volume index values in the secondary clarifier.	Low sludge volume index values are obtained due to efficient membrane treatment.
Shock Loading	Sensitive to shock loads.	Resistant to load variations. Addition of staging dampens shock loading.	Adequate resistance to shock loads as long as it does not increase the membrane fouling.
Sludge Properties	The settling properties of sludge is not always easy to control.	Good settling characteristics of the sludge.	Sludge particles have small size which makes the settling process long and may affect the effluent quality.
Recycling of Sludge	Sludge recycled to AS process.	No recycling of sludge is required because excess quality of microorganisms is available in the bioreactor.	Recycling of sludge is required to fulfil the concentration of microorganisms in the bioreactor.

After the treatment process, RBC is installed (as a polishing unit), increasing the effluent quality (Hoyland *et al.*, 2010). A hybrid RBC process improves the stability of the process against shock and toxic loads, increase the hydraulic load capacity of the process, and improve the achievable effluent quality (Hoyland *et al.*, 2010).

6.1. Membrane bioreactor

In the last decade, MBR has emerged as a mature technology competing with other conventional wastewater treatment processes. An MBR is the combination of a membrane process (microfiltration or ultrafiltration) with a biological wastewater treatment process (Vanysacker *et al.*, 2014). The prominent feature of MBR process is the better quality effluent and high removal efficiency which makes the process much more attractive (Leiknes and Ødegaard, 2007; Yan *et al.*, 2012). Compared to AS process, MBR offers several advantages which includes good disinfection capability, small footprint, less sludge production and high hydraulic loading (Yan *et al.*, 2012).

The membrane unit either can be external or submerged into the bioreactor. For the side-stream configuration, deposition of suspended solids at the surface of the membrane is reduced by high crossflow fluid velocity. This process is easy to control and membrane fouling is reduced by high crossflow fluid velocity but it is not economically feasible. High energy input makes the operational cost of the system much higher. Submerged systems, on the other hand, are economical but due to deposition of solids at the surface of the membrane, membrane fouling is the main issue (Akhondi *et al.*, 2017). Submerged system utilizes about half the energy input as compared to the side-stream system. Submerged system operates at lower permeate flux due to reduced trans-membrane pressure. This lower permeate flux increases the requirement for membrane surface area (Wang *et al.*, 2008).

MBR is a robust technology as it offers a greater removal efficiency and better effluent quality but membrane fouling restricts the performance of the membrane system. It reduces the flux, sustainability of process, increases the cleaning intervals, and ultimately increases the operational cost of the whole process (Bilad *et al.*, 2016; Bilad, 2017).

Aeration is applied to keep the microorganisms in suspension and to limit membrane fouling at the liquid-membrane interface. Aeration consumes a major portion of operational cost and yet does not result in restraining the fouling problems. Magnetically induced membrane vibration (MMV) is an alternating process to aeration which showed improved permeability, proficient fouling control and substantial energy saving (Bilad *et al.*, 2012; Mertens *et al.*, 2018). MBR is effective for the treatment of high-strength industrial wastewater. Molasses containing wastewater is considered high-strength industrial wastewater due to high COD and low biodegradability. The results showed an effective removal of 80% COD, 90% TN, and 30% color while treated with lab-scale MBR (Bilad *et al.*, 2011).

The overall performance of MBR is influenced by several factors such as membrane characteristics, operational parameters, and feed and biomass characteristics. Membrane undergoes severe drawback of membrane fouling that affects the membrane performance, decrease the membrane life-span and increases the operational cost (Bilad *et al.*, 2014).

7. RBC NOVEL APPLICATIONS

RBC provides a platform for generating energy from treating wastewater. A variety of novel processes has been applied to generate direct electricity or energy production through biogas (Sayess *et al.*, 2013). Empirical relationships and curves have been developed that are used to design the domestic and industrial wastewater

treatment systems. However, experimental data is required for different substrate substances to apply at pilot scale. Empirical relations may not produce the best results when applied at large scale. In the RBC system, the type of substrate, rotational speed, degree of submergence, number of stages, and dimensions of media are important parameters to consider to achieve optimal results. Hydrodynamics and kinetics of the process and development of biofilm should take into account while designing an industrial wastewater treatment system.

RBC system must be supported with primary treatment devices and secondary settler. An effective primary treatment removes grit, debris and grease which reduces the load on the bioreactor. The media material should be non-corrosive, resistant to environmental conditions. The performance can be enhanced with the use of supplemental aeration, baffles, and step-feeding.

8. CONCLUSION

RBC has been proved a prominent treatment process for removing BOD₅ and ammonia. The attached growth of microorganisms provides large surface area for the biodegradation of organic matter. RBC is a predominant alternative process due to the large volumetric rate, large microbial surface area, low sludge production, and less operational and maintenance cost.

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The parameters, like rotational speed, HRT, organic and hydraulic loading, DO levels, RBC media, biofilm, and waste water properties should be carefully monitored to get desired effluent quality. Thermodynamics, bio- and chemical kinetics, and biofilm characteristics need to be fully understood to fully master the RBC design. Aerobic and anaerobic RBC can be operated to achieve nitrification or denitrification. Anaerobic RBC showed the promising results for effective removal of high strength organic wastewater and nitrification/denitrification. On the lab-scale, anoxic RBC showed high nitrate removal efficiencies. Anaerobic/anoxic RBC can be used for the removal of high strength industrial wastewater and for the removal of pharmaceutical chemical. Knowledge of the dependence of various parameters on one another and improvements in disk material, supplementary aeration, and step-feeding can result in efficient treatment of wastewater.

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10. 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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