PJN
ISSN 1680-5194

PAKISTAN JOURNAL OF NUTRITION

ANSInet
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan
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Pakistan Journal of Nutrition 11 (9): 804-811, 2012
ISSN 1680-5194

Review on Moving Bed Biofilm Processes

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Abstract: The aim of this study is to present the Moving Bed Biofilm (MBB) technology as an alternative and successful method to treating different kinds of effluents under different conditions. In the past few years this technology has become more common and widely used in the world because the need for clean water is rapidly increasing as the world's population grows by each year, so many wastewater treatment facilities are needed to being expanded to provide additional capacity with least possible cost. This review covered the most important processes on MBB such as basic treatment process, kinetics of biofilm, growth and detachment of particles, modeling of MBB and affecting of carrier type and filling ratio. The review also includes many relevant researches carried out at the laboratory and pilot scales.

Key words: Moving bed biofilm, kinetics of biofilm, modeling of MBBR, basic treatment

INTRODUCTION

Today because of increased flow and organic loading many wastewater treatment plants are being expanded to provide additional capacity. The secondary treatment of the Wastewater Treatment Plant (WWTP) is usually accomplished by biological processes that can be classified as being either suspended or attached growth. The conventional and mostly used suspended growth system is represented by the classical and well known Activated Sludge process (AS). Indeed, this process can present some shortcomings when exposed to increased hydraulic and organic loads. To increase the performances of an existing AS system it would be necessary to increase the amount of biomass inside the aerobic reactor. One of these processes is activated sludge with suspended fixed-film packing, such as the Moving Bed Biofilm Reactor (MBBR).

The Moving Bed Biofilm Reactor (MBBR) process was developed in Norway during the late 1980 and early 1990 (Odegaard, 2006 and Odegaard *et al.*, 1999). In United States the first MBBR was introduced in 1995, now there are over 400 installations worldwide in both the municipal and industrial sectors with over 36 in North America.

The Moving Bed Biofilm Reactor (MBBR) represents a different spectrum in advanced wastewater treatment. MBBRs are operated similarly to the activated sludge process with the addition of freely moving carrier media (Odegaard, 2006). More specifically, in the MBBR process, biofilm grows attached on small carrier elements suspended in constant motion throughout the entire volume of the reactor and is constrained to the bioreactor through sieve arrangements at the reactor outlet (Mannina and Viviani, 2009). Advantages of the MBBR process over the Conventional Activated Sludge (CAS) process include better oxygen transfer, shorter Hydraulic Residence Time (HRT), higher organic loading rates, a higher nitrification rate and a larger surface area for mass transfer (Sombatsompop *et al.*, 2006; Chan *et al.*, 2009).

Advantage of moving bed biofilm processes: The MBBR is a complete mix, continuous flow through process which combines the advantage of fixed film and suspended growth processes, these advantage include (Metcalf and Eddy, 2003; Pastorelli *et al.*, 1999):

1. Compact units with small size.
2. Increased treatment capacity.
3. Complete solids removal.
4. Improved settling characteristics.
5. Operation at higher suspended biomass concentrations resulting in long sludge retention times.
6. Enhanced process stability.
7. Low head loss.
8. No filter channeling.
9. No need of periodic backwashing.
10. Reduced sludge production and no problems with sludge bulking.

The process of MBBR can be used as:

1. Stand-alone biological treatment process for BOD removal, nitrification and/or de-nitrification.
2. Pre-treatment system ahead of an existing activated sludge system for increased organic matter removal.

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Basic treatment process: The idea of the MBBR is to combine the two different processes (attached and suspended biomass) by adding biofilm small High Density Polyethylene (HDPE) carrier elements into the tank for biofilm attachment and growth has been proposed. This kind of system is usually referred as IFAS (Integrated Fixed-film Activated Sludge) process (Sriwiriyarat and Randall, 2005). In these systems the biomass grows both as suspended flocs and as attached biofilm. In this way, the carrier elements allow a higher biomass concentration to be maintained in the reactor compared to a suspended growth process, such as activated sludge. This increases the biological treatment capacity for a given reactor volume. Furthermore, the increase of the overall sludge age in the system leads to a favorable environment for the growth of nitrifying bacteria (Randall and Sen, 1996). Without the highly concentrated suspended bacterial population of activated sludge, the overall solids removal requirements are also reduced, allowing for the use of alternative technologies such as dissolved air flotation. In general the reactors are straightforward to install and maintain, requiring only a tank of adequate size and a bank of aerators. Odegaard *et al.* (2000) proved that the treatment performance of MBBR is proportional to the installed biofilm surface area, so treatment upgrades can be performed by simply adding additional carriers to the same tank.

The carrier elements can be installed in either anaerobic, anoxic reactor or aeration basin, the carrier media that is added for the growth of the attached biomass it can be fixed or freely moving inside the reactor. In this latter case, when the media is used on its own, the process is usually called Moving Bed Biofilm Reactor (MBBR) (Germain *et al.*, 2007). The agitation pattern in the reactor is designed to provide an upward movement of the carriers across the surface of the retention screen which creates a scrubbing effect to prevent clogging, so that the whole reactor volume is biologically active resulting in higher biomass activity. The foremost difference between the MBBR and IFAS systems is the presence of a return activated sludge stream that remains central to the IFAS process. In the MBBR process, biomass is retained in the bioreactor through attachment to suspended carrier material and retention of carrier material using sieves. Nevertheless, recently in the case of moveable carrier media IFAS have been addressed as HMBBR (Hybrid Moving Bed Biofilm Reactors) process (Di Trapani *et al.*, 2008a,b).

Ahl *et al.* (2006) proven that MBBR can process high organic loading rates at relatively short HRTs (in the range of 4 hrs) while producing consistently high quality effluent with respect to BOD, TN and TSS. Within the MBBR operation there exists three main phases according to Chan *et al.* (2009): (I) the discrete solid phase of inert carriers with immobilized microbial cells, (ii) the discrete air bubbles and (iii) the continuous aqueous phase.

Odegaard *et al.* (2000) show that the higher loading rates achievable with the MBBR system, smaller size bioreactors are often feasible, but the settleability of biosolids remains the largest challenge in MBBR design. Beside that he reported BOD removal in the range of 95% to 85% for loading rates of 15 g BOD/m^2•d to 60 g BOD/m^2•d (roughly equivalent to a volumetric loading rate of 5 kg BOD/m^3•d to 20 kg BOD/m^3•d).

According to Chen *et al.* (2008) researchers have proven that MBBR possesses many excellent traits such as high biomass, high Chemical Oxygen Demand (COD) loading, strong tolerance to loading impact, relatively smaller reactor and no sludge bulking problem.

Andreottola *et al.* (2002); Canziani *et al.* (2006) and Falletti and Conte (2007) proved that the biofilm reactors have been successfully used for treatment of dairy wastewater, landfill leachate and municipal wastewater.

Kinetics of biofilm: The substrate removal kinetics in biofilm applications is strongly dependent on the concentration of substrate in the wastewater being treated. This is illustrated in Fig. 1, which shows the development of the kinetic description from a 1’order expression at low concentrations to a 0’order expression at very high concentrations. The transition from low to very high substrate concentration is described with a ½’order expression.

As seen in the Figure, the substrate removal rate is limited by the substrate concentration only at low concentrations where a small change in concentration gives a proportional change in the degradation (Odegaard *et al.*, 2000). At high substrate concentrations the rate is limited by the diffusion of substrate into the biofilm. Thus, as the concentration increases the kinetics begins to shift from being concentration dependent to being diffusion dependent and eventually the kinetics becomes in-dependent of the substrate concentration, this is described by ½’order kinetics (Odegaard *et al.*, 2000). At very high substrate concentrations the enzymatic efficiency restrains the removal rate - 0’order dependence (Odegaard *et al.*, 2000).

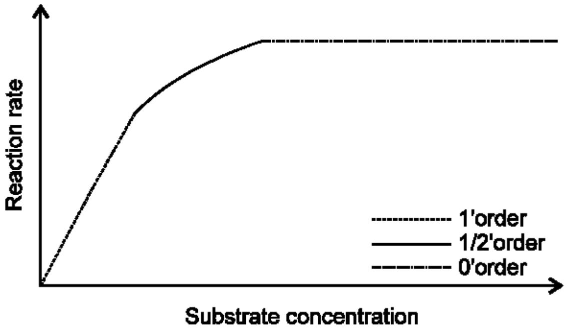


Fig. 1: The kinetic description with reaction rate as a function of the substrate concentration (Henze *et al.*, 1997)

Although the kinetics in biofilm processes is normally described as above, it should be pointed out that the composition of the substrate in the wastewater will determine its kinetic characteristics (Odegaard *et al*., 2000). Diffusion is believed to be the most important mass transfer phenomenon and is thus normally considered in kinetic descriptions (Larsen, 1992). Other transport mechanisms such as advective transport, on the other hand, are usually not regarded (Larsen, 1992).

Growth and detachment of biofilm: The majority of carbon input to wastewater treatment plants constitutes particulate organic matter in the form of slowly biodegradable organic matter (Insel *et al*., 2003). Particles entering a MBBR are either degraded by micro-organisms in the biofilm or pass straight through the process. The particles may be completely degraded and taken up by microorganisms but they could also be partially degraded and then released back into the bulk liquid. The size of the organic fragments resulting from the degradation determines whether the microorganisms in the process may utilize the degradation products directly. A fraction of the partially degraded particles will join the under graded particles that pass straight through the process, most of the partially degraded particles are however likely to come in contact with the biofilm again for further degradation. Completely degraded substrate is transported through the bacterial membrane, where it is used for respiration and production of new biomass. Almost 50% of the energy in the substrate is bound in new biomass (Jonstrup *et al*., 2010). Biomass eventually detaches from the carrier surface mainly due to shear forces and degradation in the interior of the biofilm. Thus, to some extent, biodegradation transforms organic matter in influent water to particles of biomass.

In a MBBR process, degradation of particulate organic matter is aided by extracellular enzymes produced by the microorganisms present in the process. Complete degradation of individual particles as well as partial degradation of several particles is catalyzed by extracellular enzymes. Further, out of 197 identified extracellular enzymes, 145 have been found to be hydrolytic (Dimock and Morgenroth, 2006). The hydrolytic enzymes are either attached to the bacterial membrane or suspended in the bulk liquid (Confer and Logan, 1998). Complete degradation of more complex particulate organic matter such as polysaccharides may require a mixture of hydrolytic enzymes (Haldane and Logan, 1994). The large number of hydrolytic enzymes is therefore essential for the microorganisms in wastewater to be able to utilize a wide range of organic compounds.

Bacterial production of enzymes is normally stimulated by environmental factors such as substrate availability, but in some cases the production of enzymes carry on regardless of external effects (Larsen, 1992). Further, Goel *et al*. (1999) found that the synthesis of enzymes is influenced by the oxygen level, while already synthesized enzymes are unaffected by the availability of oxygen. The hydrolysis rate is however independent of the oxygen level according to the results presented by Goel *et al*. (1999).

Boltz and La Motta (2007), find that the organic particulates attach to the biofilm surface due to bioflocculation. Further, Boltz and La Motta (2007) regard bioflocculation in biofilm reactors and particle bioflocculation in activated sludge reactors as similar processes and thereby validate the hypothesis that the Extracellular Polymeric Substances (EPS) in the biofilm bind particles with results from studies on activated sludge performed by La Motta *et al*. (2004). Bioflocculation is a process in which chemical bonding arises between the EPS and the organic particulates. The particles are then hydrolyzed by extracellular enzymes and the hydrolytic fragments are, depending on their size, either taken up by the microorganisms in the biofilm or released to the bulk solution. This is consistent with the results from several other experiments, which demonstrated that hydrolysis of proteins and polysaccharides occurs in contact with biofilm or sludge flocs in activated sludge (Confer and Logan, 1998). However, with increasing molecular weight the diffusion into the EPS becomes limiting, which results in a relocation of the hydrolytic activity from the membrane surface to the EPS constituting the biofilm surface.

Dimock and Morgenroth (2006) suggests that the microorganisms presumably release enzymes into the EPS. By excreting extracellular enzymes into the EPS, the microorganisms would increase the rate at which high molecular compounds are hydrolyzed and consumed. Also, the EPS is flexible and can enfold larger particles, which are thereby accessible to hydrolysis by the enzymes in the EPS.

Of the organic substances consumed in a wastewater treatment process one part is used for biomass production while the other is used for respiration. The oxygen used for respiration can be determined by measuring the decrease in oxygen level in the process when no air is supplied. By calculating the slope of the oxygen concentration curve during several unarerated intervals, the Oxygen Uptake Rate (OUR) and oxygen consumption connected to respiration is found. OUR can be used to determine for instance the performance of a treatment plant and wastewater characteristics and combined with additional analytical methods more information can be retained about the processes (Hagman and La Cour Jansen, 2007).

According to Briones and Raskin (2003), biofilms can be comprised of any type of microorganism, including algae, fungi, bacteria, achaea and protozoa/metazoa and

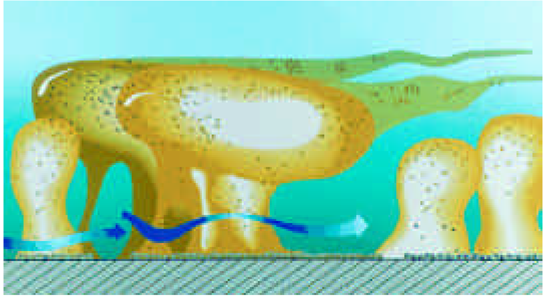


Fig. 2: Diagram of biofilm structural heterogeneity. “Mushroom-Istructure" (Rodney and William, 2002)

in most natural and engineered biofilms the microbial community is complex with multiple species. While many general principles of microbial ecology apply to biofilms, biofilm communities have several unique features that influence their microbiology and community dynamics. These include the presence of substrate diffusion gradients causing stratification and clustering of species and the cell density dependant signaling mechanisms (quorum sensing) that govern fundamental genetic regulatory pathways. Some of the work to characterize biofilm heterogeneity led to a generalized concept of biofilm structure as a collection of “mushroom”-like microcolonies with open channels between the “stalks”, promoting fluid flow to deep regions of the biofilm (Fig. 2).

Flemming and Wingender (2001) show that the Extracellular Polymeric Substances (EPS) are polysaccharides, proteins, lipids and nucleic acids that have been observed to accumulate on the surfaces of bacterial cells. These biopolymers are produced by most types of microorganisms (including bacteria, archaea, fungi and algae), in a variety of environments.

One of the interesting features of the MBBR is the importance of the detached suspended phase, making the reactor not exclusively a biofilm or suspended phase system, but rather a hybrid. Biofilm detachment is the process by which material from the biofilm breaks free and enters the suspended phase. Detachment is a complex phenomenon based on physical-chemical interactions of EPS and microbes at the cellular level as well as biologically mediated processes such as those discussed in the section on quorum sensing.

Modeling of MBBR: Even with their increasing application, moving bed biofilm reactors have been the subject of limited modeling research. Although a significant body of performance data has been published to guide reactor sizing and design, modeling has been used only to a limited extent to explore the fundamental processes that govern reactor behavior. Given the preceding discussion of evolving approaches to model biofilms, there is potential to gain insight into this hybrid reactor system. The complex features of biofilms make them more challenging to describe mathematically than suspended cultures. Specifically the diffusion gradients of substrates, structural heterogeneity and detachment phenomena add complexity to traditional approaches to predict the kinetics and growth of microbial communities. Biofilm models can be divided into three general categories that may be most suitable (Wanner *et al*., 2006):

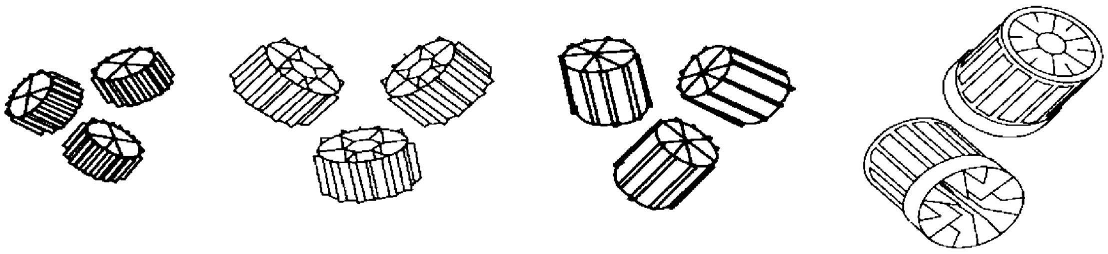
1. Empirical or semi-empirical models.
2. Theoretical diffusion-reaction models. These are typically described by a system of differential or analytical equations based on average biofilm properties.
3. Discrete cellular automaton models. These are evolving simulations in a theoretical grid of space with biofilm cells that propagate into neighboring gridpoints according to algorithms tied to kinetic parameters.

Trapani *et al*. (2010) showed the results of a respirometric technique study to estimating the kinematic heterotrophic constants in the HMBBR pilot plant.

Boltz *et al*. (2009) was developed a model of Integrated Fixed-film Activated Sludge (IFAS) and Moving-Bed Biofilm Reactor (MBBR) systems. The model was based on theoretical considerations that include: simultaneous diffusion and Monod-type reaction kinetics inside the biofilm; competition between aerobic autotrophic nitrifiers, non-methanol-degrading facultative heterotrophs, methanol-degrading heterotrophs; slowly biodegradable chemical oxygen demand and inert biomass for substrate (when appropriate) and space inside the biofilm and biofilm and suspended biomass compartments, which compete for both the electron donor and electron acceptor. The model assumed identical reaction kinetics for suspended biomass and biofilm bacteria.

Boltz and Daigger (2010) also studied uncertainty in bulk liquid hydrodynamics and biofilm dynamics in biofilm reactor design. They considered the uncertainties of liquid hydrodynamics on biofilm thickness control, surface area and development and the biofilm dynamics influence on biofilm structure, thickness and function. From a substrate transformation perspective, the mass transfer by diffusion limitation in biofilm reactors controls, while the suspended growth systems are kinetically or biomass limited.

Affecting of carrier type and filling ratio: Odegaard *et al*. (1994) showed that the MBBR system consists of a reactor vessel containing mixed liquor suspended solids with specially designed carrier media suspended and kept in constant circulation. A screen is provided at



KMT (K1) KMT (K2) AWT ANOX

Fig. 3: The main four biofilm carriers (Odegaard *et al*., 1994)

the outfall end of the reactor to keep media from clogging the effluent spout or passing out of the reactor. Experiments are currently underway to increase the carrier media size. This will enable screens with larger openings to be used and thus prevent the use of primary settlers in most MBBR system configurations.

The carrier medium is made of polyethylene and has a specific gravity less than 1. The density of the medium is critical as it allows it to move freely within the reactor even at filling fractions (i.e. The media volume usually does not exceed 70% of the reactor volume). The carrier elements allow a higher biomass concentration to be maintained in the reactor compared to a suspended growth process, such as activated sludge.

According to Odegaard *et al.* (2000), the fundamental characteristic of the MBBR is the specially designed biofilm carriers, for which the geometry, sizing and materials of construction have been considered carefully to maximize performance. This is a key difference from the activated sludge process where treatment performance is more directly tied to reactor volume. In the MBBR, surface area can be increased by designing carriers with a higher specific surface area or by adding a greater quantity of carriers to a reactor volume. This offers flexibility for future treatment capacity upgrades without requiring the construction of additional reactors.

There are several different sizes and designs of carrier elements used in the MBBR process. Carrier media geometry to promote attached growth has included smooth cylinders (Andreottola *et al*., 2002; Yang *et al*., 2010), cylinders with internal crosses and external fins (Odegaard, 2006), rectangles and cubes (Golla *et al*., 1994 and Valdivia *et al*., 2007) and spheres (Valdivia *et al*., 2007). Furthermore, various materials have been employed for biomass support including porous ceramic (Valdivia *et al*., 2007), reticulated foam (Golla *et al*., 1994 and Valdivia *et al*., 2007), Polyvinyl Alcohol (PVA) (Levstek and Plazl, 2009), polyurethane (Ngo *et al*., 2008), plastic foam (Valdivia *et al*., 2007) and high density polyethylene (Odegaard, 2006). The main four carriers shape are shown in Fig. 3. The KMT carrier K1 is the original kindles carrier that is mostly used. buoyancy differences. The surface areas are estimations to the best of our ability. The total surface area consist of both inner and outer surfaces, while the effective surface area is that where biofilm seems to attach. The effective surface area of the KMT K1 and the AWT carriers were calculated as the whole inner area plus the area of the outer fins. The area between the fins was not included since visual inspection did not show any sign of growth here. For the ANOX carrier, the effective area is calculated as the inner area since there are no fins with outer area. Mixed relationships have been presented in the literature in terms of the recommended filling fraction (carrier volume versus total bioreactor volume).

Odegaard (2006) recommends a filling fraction below 70% for cylindrical plastic carriers to allow for smooth unimpeded suspension of moving bed media.

Di Trapani *et al.* (2008a,b); Mannina and Viviani (2009) analyzed the nutrient removing performance of moving bed bioreactors at 33% and 66% filling ratio and noticed little performance variation in terms of wastewater constituent removal.

Canziani *et al.* (2006) successfully used plastic media at a filling fraction of 37.5% for landfill leachate post-denitrification treatment after membrane filtration. For enhanced nitrification/denitrification of a municipal wastewater treatment plant.

Falletti and Conte (2007) recommended a 43% filling fraction with plastic cylindrical media. Levstek and Plazl (2009) found similar nitrification rates and required basin volume for plastic cylindrical media at a filling fraction of 37% and for PVA-gel carriers at a filling fraction of 9.6%. This highlights the potential that specific surface area may also be an important design parameter.

Xiao and Ganczarczyk (2006) found that at a filling fraction of 70% the attached growth density is 5 to 13 times higher and responds more strongly to COD influent as compared to that of activated sludge flocs found in suspended growth CAS systems. Obviously there exists a large disconnect in the research community concerning media geometry, material and filling fraction. Future research should focus on the effect of these parameters for nutrient removal, microbial biocenosis and fouling propensity in moving bed bioreactors.

Odegaard *et al.* (1994) proved that the high specific area of the carrier media, which allows very high biofilm concentrations in a small reactor volume, controls the system performance. He reported that typical biofilm concentrations range from 3000 to 4000 g TSS/m^3, which is similar to values obtained in activated sludge processes with high sludge ages. It was inferred that, since the volumetric removal rate in the MBBR is several times higher than that in the activated sludge process, the biomass in the former are much more viable.

Zhao *et al.* (2006) used the laboratory-scale, continuous-flow MBBR with internal circulation through aeration for the treatment of municipal wastewater. The attached film was a mixed-microorganism consortium, which used composite-refined-diatomaceous earth as novel biomass carriers to form a Diatomaceous-Earth-Moving-Bed-Biofilm-Reactor (DEMBBR) process. He reported that the continuous-flow reactor was successfully achieved without seeding activated sludge. The DEMBBR process removed chemical oxygen demand, total phosphorus, ammonium-nitrogen and turbidity at the highest rate of 88.5, 83, 92.3 and 96.7%, respectively, with a hydraulic retention time of only 2.5 hrs.

Levstek and Plazl (2009) studied the influence of carrier type on nitrification in the lab-scale moving-bed biofilm process by used two different types of carriers. One of the carriers used was a cylindrical high-density polyethylene ring shaped carrier (AnoxKaldnes, K1 carrier) and the other was a spherical Polyvinyl Alcohol (PVA) gel bead shaped carrier (Kuraray, PVA-gel carrier). He conclude that it is difficult to compare the efficiency of the carriers because they are used at different filling fractions and in different reactor volumes and also because it is claimed that nitrification in the PVA-gel beads also takes place inside the bead and therefore that the effective area of the beads is not known. K1 carrier and PVA-gel beads, revealed about the same maximal nitrification, i.e. for K1 carrier up to 3.5 gNH$_4$-N/m^2.d and for PVA-gel beads up to 3.1 gNH$_4$-N/m^2.d at 208C.

Conclusion: Based on the review the following conclusions can be drawn:

1. Today the need for clean water is rapidly increasing as the world's population grows by each year. So it is necessary to expanded all the wastewater treatment facilities to provide additional capacity because of increased flow and organic loading. In the last years the MBB technology becoming increasingly popular and widely used in the world to treating different kinds of effluents under different conditions because the idea of the MBBR is to combine the two different processes (attached and suspended biomass), by this way, the carrier elements allow a higher biomass concentration to be maintained in the reactor compared to a suspended growth process, such as activated sludge. This increases the biological treatment capacity for a given reactor volume.
2. Because there is a need to investigate how the bio solids dynamics are influenced by process changes relevant to applied wastewater treatment systems and suggest new routes to reactor design and optimization, the biofilm growth, detachment and modeling of MBBR are continue to draw significant research attention.
3. The fundamental characteristic of the MBBR is the specially designed biofilm carriers, for which the geometry, sizing and materials of construction have been considered carefully to maximize performance.

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