Chapter

Biofilm in Moving Bed Biofilm Process for Wastewater Treatment

Shuai Wang, Sudeep Parajuli, Vasan Sivalingam and Rune Bakke

Abstract

A brief introduction of the long history of biofilm-based wastewater treatment is given together with basics of biofilm behavior and mechanisms in removal and transformation of pollutants. Moving bed biofilm reactor (MBBR) principles and applications of such are presented. Advantages and limitations of such solutions are given together with evaluations of emerging MBBR applications. The basis of biofilm processes and biofilm layer classification based on dissolved oxygen gradient is discussed. Organisms grow at the protected surface of the biocarrier where oxygen gradients create aerobic, anoxic, and anaerobic layers allowing simultaneous nitrification and denitrification in one MBBR (nitrification, nitritation, autotrophic, and heterotrophic denitrification). Combination of MBBR with activated sludge, continuous flow intermittent cleaning (CFIC®), and integration with anaerobic digestion increases the potential usage of MBBR for enhanced efficiency and energy recovery and is partly discussed as case studies (COD, ammonium, and solid removal). Biofilm thickness and scaling control can be crucial for MBBR performance. The type of carriers, filling degree, and operational conditions play a major role for process performance; hence, the effect of those parameters is presented.

Keywords: moving bed biofilm, TN removal, scaling on biofilm, biocarriers

1. Introduction

The use of biofilm systems in wastewater treatment is being increased rapidly because of its tempting approach of pollutant removal from wastewater, which has been proved to be effective in terms of both cost and environmental perspectives [1, 2]. Biofilm can have both positive and negative effects in treatment processes depending on the type of treatment concept applied. Processes such as a moving bed biofilm reactor (MBBR) depend on biofilm development, while it can cause problems in membrane bioreactor (MBR) through membrane biofouling. Those processes taking advantage of biofilms have been widely used for the removal of organic and inorganic matters from different wastewaters [1], by mechanisms such as biodegradation, bioaccumulation, biosorption, biomineralization, and bio-immobilization [1, 3, 4].

There are several benefits of using biofilm system in wastewater treatment, as compared to suspended growth system (activated sludge for example), such as flexible procedures, smaller space demand, lower hydraulic retention time, increased resilience to changes in the environment, higher biomass retaining period, high active biomass concentration, as well as low sludge production [3, 5, 6]. The use of biofilm systems also enhances the control of reaction rate and population mechanisms [5, 7].

Microorganisms tend to form clusters/colonies to expedite the organism's growth and facilitate access to food, etc., by forming biofilm [8]. In biofilm or attached growth systems, the growth of the biomass responsible for the conversion of organic material and/or nutrient occurs on the surface of support packing material [9]. Biofilm formation is enhanced by substratum provided to retain and grow microorganisms. The support medium can be rocks, stones, gravels, sand, soil, wood, rubber, plastic, and agglomerates of the biomass itself (granules) or any other synthetic materials [3, 8]. The packing material provides a large surface area per unit volume for biofilm development in high-rate processes; thus, substratum material selection is important to maintain a high quantity of active biomass and to uphold different varieties of microbial populations [10]. The large surface area of the biofilm enables the media to efficiently adsorb a high amount of substrates from the influent wastewater. As the biofilm develops on the media, it provides diverse habitats so that different constituents such as carbon and nitrogen components of the wastewater are transformed and mineralized, thus increasing the removal efficiency of the organic substances from influent wastewater.

There are generally three steps involved in biofilm formation, including biofilm attachment, growth, and detachment (**Figure 1**). Microorganisms attach on to the substratum, such as the surface of carriers in MBBR processes, by adhesion, and the attachment is reversible at the early stage. Tight connections between organisms and the substratum can be gradually established by extracellular polymetric substances (EPS) produced by the organisms. EPS is a mixture of polysaccharides, proteins, and extracellular DNA, and it is recognized to also be important for the communication between biofilm cells, biofilm 3D structure formation, and multicellular living [11]. Biofilm detachment from the surface is a natural mechanism where biomass (individual cells or lumps of cells) is released into bulk liquid. It can be influenced by hydrodynamic shear forces and other environmental conditions such as toxic chemical exposure. Detachment process limits biofilm accumulation and thickness and thus balances the attached biofilm quantity at steady-state conditions [11].

Different species can be found in the same biofilm clusters. They can vary from rapidly growing to inactive organisms, from heterotrophic to autotrophic organisms depending on substrate gradients, mutation, genetic regulatory switches, and signaling pathways [11]. Due to oxygen transfer limitations in an aerated system, the biofilm can contain aerobic, anoxic, or anaerobic organisms at the same time [5, 8]. A well-established biofilm can have any thickness, but around 0.1 mm is considered

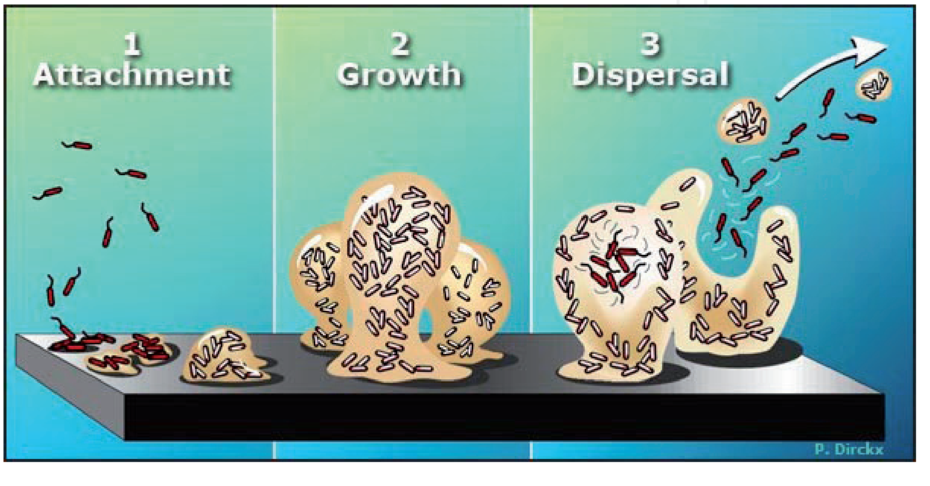

Figure 1.
Biofilm life cycle. Adapted from the Center for Biofilm Engineering, Montana State University [11].

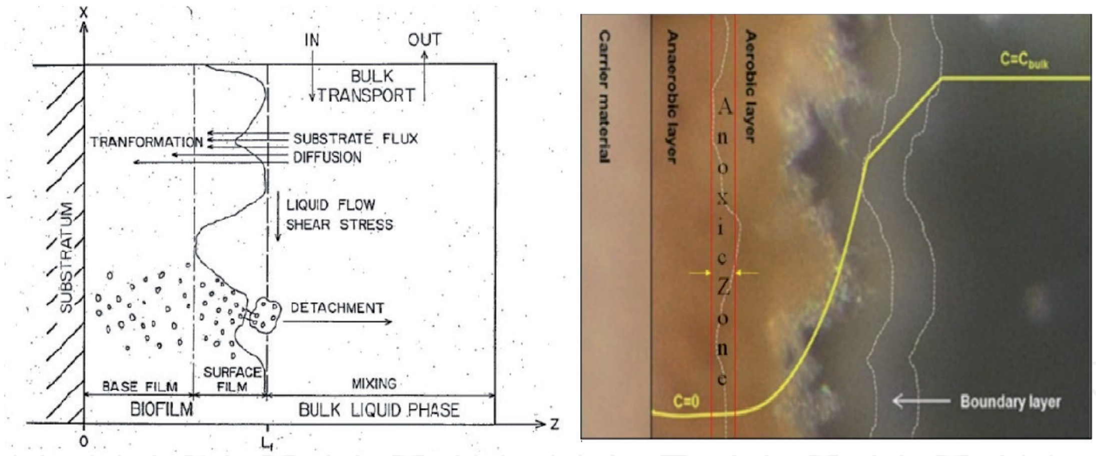

Figure 2.
Left, graphical illustration of biofilm processes [15]; right, biofilm picture and layer classification based on dissolved oxygen gradient [12].

suitable in an efficient MBBR, where mass transfer in the biofilm structure and between the interphase of biofilm and liquid is critical for efficient mass transfer [12, 13]. Both diffusion and convention can occur [11, 14] in the biofilm mass transfer (**Figure 2**), while substrate diffusion is considered to usually be the rate-limiting process within the biofilm structure. Substrate accessing of biofilm can be enhanced by, for example, enhanced aeration/mechanical mixing to enhance mass transfer from the bulk liquid to the biofilm surface. The internal biofilm growth (**Figure 1**) and external forces such as abrasion are important factors for biofilm morphology, development, and effectiveness of biofilm processes.

Biofilm processes applied for wastewater treatment have a long history. Trickling filters (TF) and rotating biological contactors (RBCs) utilizing biofilm growing on the packing medias are biofilm processes being widely applied of low-cost and low maintenance comparing to activated sludge process [1, 3, 16]. Moving bed biofilm process, which was developed in the 1980s [14, 17], has been widely applied for organic and inorganic wastewater treatment of high efficiency, low maintenance, and low operation cost [8, 17, 18]. A membrane-aerated biofilm reactor (MABR) has been developed recently for organic and ammonia removal, based on an aerated membrane where biofilm attaches on the fiber [10]. Biofilm in the form of granular sludge for energy recovery (methane) from wastewater organics, such as by upflow anaerobic sludge blanket (UASB) [8, 19], expended granular sludge bed (EGSB) [20, 21], and internal recycle reactor (IC) [22], and aerobic granular sludge reactors for shortcut ammonia removal, such as anammox process [23], and for simultaneously organic, phosphor, and ammonia removal, Nereda [24] has been developed and is increasingly used in both industrial and municipal wastewater treatments.

Biofilm applied in MBBR processes are focused in this book chapter. Commonly applied MBBR and its derivatives processes are introduced and compared. A case study based on MBBR concept for municipal wastewater treatment is also provided.

2. Moving bed biofilm reactor

Moving bed biofilm reactor (MBBR) is an advanced wastewater treatment technology, which employs the benefits of both biofilm and activated sludge processes for highly efficient wastewater treatment [14]. Developed in the 1980s, MBBR has been established in the last two decades worldwide as a simple, robust, flexible, and compact wastewater technology for both municipal and industrial wastewater treatment [14].

2.1 Biocarriers

Plastic carriers of different shapes and surface areas have been developed and applied in the MBBR systems as biofilm substratum. The carriers' shape, density, protected areas, and void volume are important factors that affect the performance of MBBR processes. Carriers can be made of different shapes such as squares, round, and sphere. The shape can affect the carrier's strength, shearing, and colliding conditions. The carrier density is normally lower than water at around 0.98 kg/L, so that it can be suspended in wastewater with biofilm attachment without introducing strong mixing. The carriers protected areas range from 300 to over 1000 m^2/m^3 depending on the shapes and internal structure. Large carrier protected areas normally mean high complexity of the carrier structure and higher production cost. Carriers of protected areas of 500–1000 m^2/m^3 are normally applied in full-scale wastewater treatment plants due to their costs and process benefits. **Figure 3** shows two different types of plastic carriers that are made of high-density polyethylene (HDPE) with respective protected surface area of 650 (BWTX®) and 828 (BWT15®) m^2/m^3. The biofilm on carriers develops as illustrated in **Figure 1** and maintains active organisms in thin layers. A well-designed carrier enables stable biofilm in the MBBR process, so that the void is not easily blocked by wastewater particles or excessive biofilm accumulation. Effective mixing/aeration combining a good carrier design leads to good system performance and low-maintenance requirements.

2.2 Carrier filling degree

A typical MBBR process can have a biocarrier filling ratio lower than 70%, where carriers are continuously mixed in the reactor and the whole reactor has homogenous conditions. Due to shear forces from mixing/aeration, biofilm growth and detachment processes are balanced to maintain a relatively constant biofilm thickness at steady-state condition. The limitation of filling degree is related to energy consumption and mixing effects for mass transfer purposes [26]. Higher filling degrees will result in higher energy requirement for sufficient mixing of the suspended carriers. It is especially challenging for aerobic systems where aeration energy consumption can account for more than 70% of the complete treatment energy demand [8, 13]. While different carrier filling degrees have been attempted, a different setup based on over 90% filling degree has been developed by biowater technology. The process is named continuously flow intermittent cleaning (CFIC®) which constitutes of two individual modes, a normal operation mode and a washing mode. In the normal operation, over 90% filling degree leads to an almost stagnant

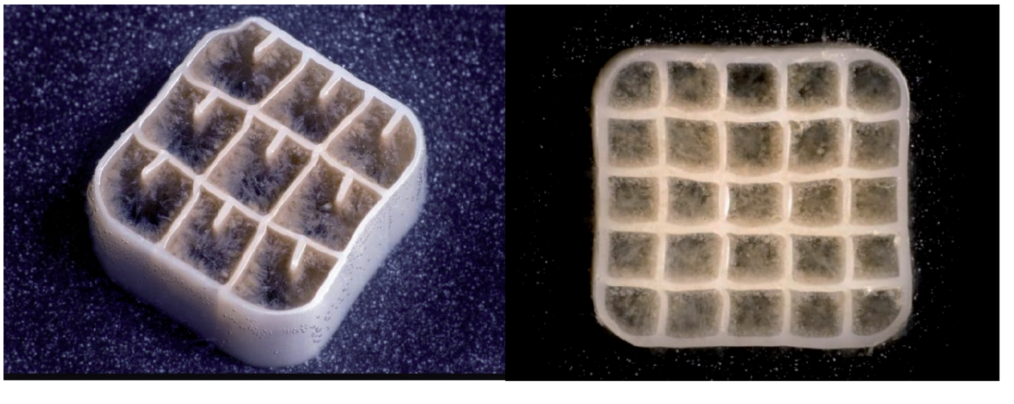

Figure 3.
Biocarrier BWTX® (left) and BWT15® (right) (biowater technology AS, Norway) with biofilm growth [25].

carrier bed. Oxygen field transfer efficiency (OTE) has been documented to be 1.5 times higher than in a normal MBBR with lower filling degree by applying coarse bubble aeration. Big bubbles are cut through the carrier bed with better utilization. Due to high filling degree, sludge will accumulate on carriers which also work as a filter bed media for wastewater treatment. High sludge accumulation will lead to effluent solid increase after certain times depending on load situations. A washing mode is therefore introduced by increasing the water level in the reactor which resembles a normal MBBR operation washed-out accumulated excess sludge (similar to backwashing of sand filters). Wastewater can be fed continuously to the reactor without stops during the washing cycle. This high filling degree process has been applied in full scale for petrochemical wastewater treatment [27] and municipal wastewater treatment both in China and Brazil for organic and ammonia removal, confirming high efficiency and compactness. Carrier filling degree around 30% is also applied for systems to remove dissolved oxygen before feeding to a denitrification system, for example.

2.3 MBBR treatment process

In a MBBR biofilm system, the process effectiveness depends on the active organism's concentration, mass transfer efficiency, and system setup, for example, feed distribution and mixing. Organisms' concentration is relatively constant in a stable process, depending on feed substrates and biofilm mass on carriers, which is on average below 20 g/m^2. The carrier mass value can be higher in a system with scaling, for example, while the active organisms are mainly on the outer surface of the scaling mass. For processes like nitrification or anammox, the mass per area can be lower due to the slow growth rates. The organic loading rate in MBBR is generally based on the protected surface areas, such as gCOD/m^2/d. The organic loading rate can be as high as 100 gCOD/m^2/d depending on the biofilm condition and loading history. A reduced removal efficiency is expected in such high load system where oxygen supply can be a limiting factor. Comparing to activated sludge system, a MBBR can sustain higher sludge concentration per reactor volume. With an on average 20 g/m^2 biofilm on carrier surface and a filling degree of 70%, the sludge content is about 7 g/L for a surface area 500 m^2/m^3 carriers. This is achieved without sludge return and thus reduces the operation complexity and equipment for sludge return is avoided.

MBBR process has also been developed for ammonia removal through both traditional nitrification and denitrification processes and anammox (**Figure 4**) [13]. In conventional nitrogen removal process, ammonium ion is oxidized to nitrate by complete nitrification, and subsequently nitrate is reduced to nitrogen gas by pre-/post-denitrification. Such nitrogen removal is usually carried out in two different reactors. Inorganic carbon as alkalinity is normally supplied to perform ammonium oxidation. Denitrification requires easily degradable organic such as methanol as electro acceptor. Partial nitrification, called nitritation, and anaerobic ammonium oxidation can also be achieved to remove nitrogen from wastewater in one reactor by manipulating dissolved oxygen concentration into the biofilm. That means oxidation of nitrite to nitrate is suppressed, and denitrification can occur according to "shortcut" in **Figure 4** [13].

Ammonium removal by nitrite is performed by a group of autotropic bacteria, named anammox bacteria [28, 29]. The anammox process requires 40% less energy and generates 88% less CO_2 emission comparing to traditional nitrogen removal process [10, 24]. Due to low growth rate (0.06 g VSS/g VSS d), a doubling time being ~10–14 days at relatively high temperature (30–35°C) [30], anammox requires long start-up period. The biofilm attached to the MBBR carrier, being protected from the environment, maintaining long sludge retention time,

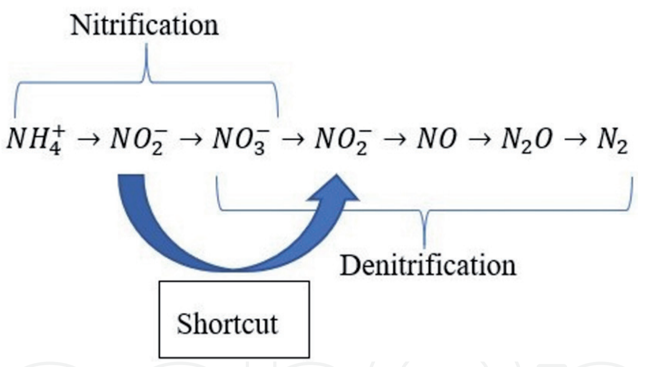

Figure 4.
Nitrification and denitrification with shortcut mechanism illustrated [13].

and thereby preventing the slow-growing organisms from being washed out of the system, is suitable for slow-growing anammox biomass. Limited research on anammox process in MBBR is documented, but it has been observed that removal rates of up to 1.2 kg N/m^3.d can be achieved using MBBR for side-stream reject wastewater treatment in municipal application [31]. Nitrite formation is a limiting step, and dissolved oxygen needs to be well controlled, so advanced process control is required for efficient MBBR anammox solutions.

MBBR has also been applied for biological phosphor removal in Norway by physically moving carriers with biofilm from anaerobic stage to aerobic stage and back to anaerobic stage so that the P-accumulating organisms undergo the same cycles as in activated sludge "Bio-P" processes [32].

2.4 Different MBBR reactor setups

Due to MBBR's compact nature, high effectiveness, and reliability, the MBBR process is also integrated with other processes (summarized in **Table 1**), such as with activated sludge for enhancing ammonia removal, with anaerobic granular sludge process to form a hybrid system, such as HyVAB® [13, 27], for combined anaerobic and aerobic wastewater polishing, and with membrane bioreactor (MBR) for high strength and stricter wastewater treatment requirements [10].

Based on the MBBR technology, there are several commercially proven technologies available in the market [25], such as:

- CFAS®—Combined fixed film activated sludge
- CFIC®—Continuous flow intermittent cleaning reactor
- HyVAB®—Hybrid vertical anaerobic biofilm reactor

The typical layout for the above processes for organic removal is shown in **Figure 5**. **Table 1** briefly compares the abovementioned technologies and key benefits. Most of the technologies only focus on COD and nutrient removal from wastewater except HyVAB®. HyVAB® is the technology that focuses on both COD, nutrient removal together with energy recovery as biogas [13, 25]. Biogas production from the HyVAB® reactor makes the treatment process partially or fully energy self-sufficient.

2.5 MBBR operational issues

Depending on MBBR process operational knowledge and full-scale design experience, several problems can be encountered for a full-scale MBBR process, such as

Technology	Process	Benefits
MBBR [12, 13, 25]	Freely moving plastic carriers with attached biofilm removing both organic and inorganic nitrogen	• High effective surface area in carrier gives large protected growth area, hence less space requirement • Self-regulating biofilm on carriers requires less monitoring and ensures stable treatment process
CFAS®/IFAS [33]	Uses the existing activated sludge process together with MBBR carriers, by introducing plastic carriers into the activated sludge process	• Suitable for retrofitting existing activated sludge plant to enhance nitrification and BOD removal • Small foot print • BOD, P, and N removal can be achieved together • Achieve low SVI, ensures efficient sludge removal
CFIC® [34]	High carrier filling degree of over 90–99% that allows high substrate transfer efficiency. Operates in normal and washing modes with continuously wastewater feeding. Excess biomass removal is needed	• Very compact and energy-efficient process (20% smaller footprint and 50% less energy demand than MBBR) • Higher oxygen (1.5 times to MBBR) and substrate transfer efficiency • Very low SVI enables fast sludge settlement, 80% less effluent sludge than MBBR in normal mode
HyVAB® [27]	Hybrid system integrates both anaerobic and aerobic high-rate processes. Anaerobic stage recovers energy (methane) from wastewater and the aerobic part with biocarrier removes the remaining organics and nutrients	• Ultra-high rate and compact process • Suitable for wide range of application; reject water treatment and industrial wastewater treatment • Very low sludge production • High COD removal and generate high methane content biogas

Table 1.
MBBR integrated technologies with other biological treatment process.

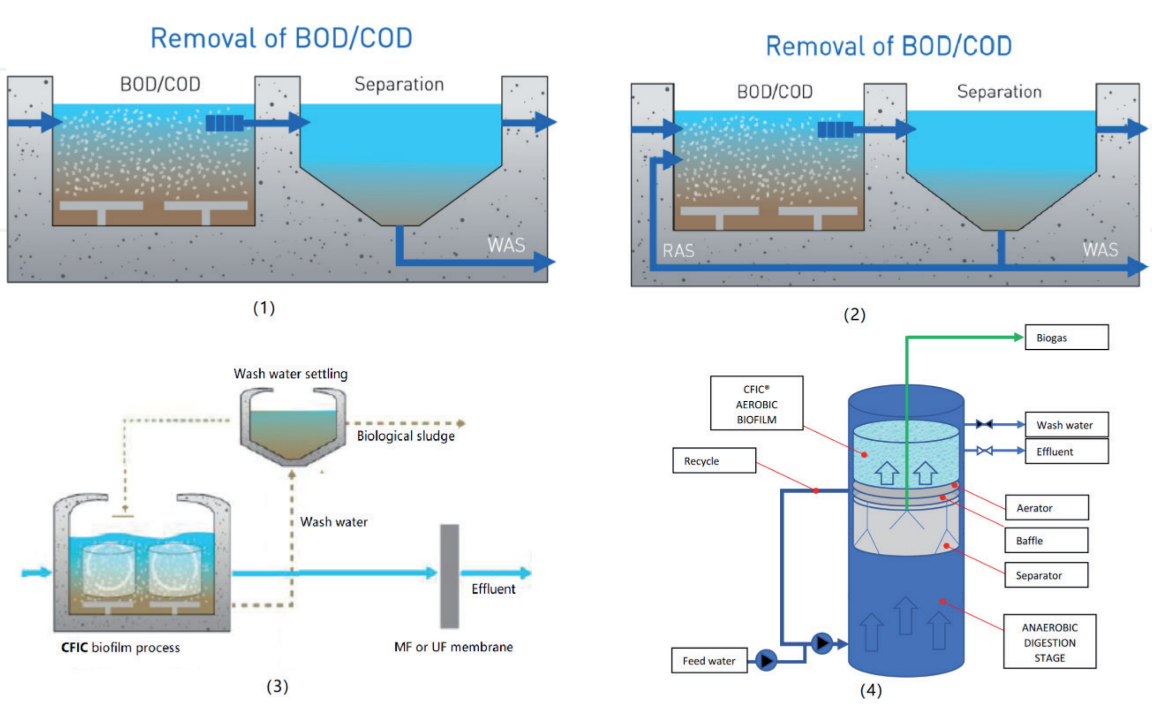

Figure 5.
Typical layout of (1) MBBR, (2) CFAS, (3) CFIC, and (4) HyVAB for organic (BOD/COD) removal [25].

feed pipe/effluent sieve blocking, nonhomogeneous mixing, carrier voids blocking, destroyed carriers, carrier accumulating at the effluent sieves, and carrier overflow out of reactor. These can be all prevented through skilled design, based on accumulated project knowledge and operation experience.

Depending on wastewater characteristics, problems such as chemical scaling on carries can happen, especially for wastewater that contains high calcium, ammonia, and other minerals, such as anaerobic digestion reject water and diary wastewater [35]. Mineral precipitation can occur when wastewater is supersaturated with relevant ion concentration [35]. The composition of mineral scaling varies and can contain struvite, hematite, hydroxyapatite, maghemite, etc. [8, 35]. Scaling on biofilm carriers creates negative effects on the reactor's performance by reducing effective surface area, hindering the mass transfer, and demanding more energy to keep the carriers in suspension. Carriers with excess scaling become heavier and settled down at the reactor bottom and need to be replaced [35]. The pH and concentration of the ions are the main factors influencing chemical precipitates on carriers. Minerals tend to precipitate more at higher pH; thus, pH control can alleviate scaling. Buffer dosing, reduced air stripping of CO_2, and alkalinity removal could help to hinder scaling rates. Pure oxygen aeration is an option to avoid air stripping of CO_2 to avoid pH increase. Pretreatment by chemical precipitation such as adding lime to remove calcium and magnesium could also be an option.

Feed wastewater composition changes can cause disturbances such as increased organic load in nitrification or anammox processes that will lead to a shift in competition between heterotrophic to autotrophic bacteria. In such cases, the heterotrophic bacteria that have higher growth rate can gradually dominate the MBBR biofilm, leading to unfavorable condition for ammonia removal.

Unwanted biofilm detachment caused by toxic chemicals or abrupt operational condition changes, such as sudden increase of aeration can lead to process problems and even failure in extreme cases, but inner layers of biofilms are protected by the outer layers, making biofilms quite resilient to such disturbances.

3. MBBR case study

This chapter provides a case study where the novel CFIC biofilm process has been studied for municipal wastewater treatment, including for organic, ammonia, and total nitrogen removal. The CFIC process operates in two modes, a normal operation where high carrier filling is applied and a washing mode for extra sludge removal (**Figure 6**). Detailed process concept description can be referred to [34], and more information is given in the following presentation of a three-stage CFIC pilot for municipal organic and nitrogen removal. The first full-scale three-stage CFIC process has also been accomplished for a 30,000 m^3/d municipal wastewater treatment in Guiyang, China, in 2017.

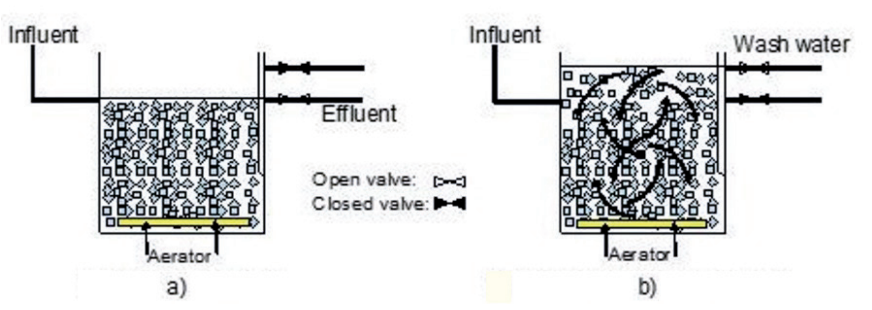

Figure 6.
The CFIC® during (a) normal operation and during (b) the cleaning cycle.

3.1 Pilot layout

A pilot CFIC plant with a maximum feeding capacity of 6 m^3/h has been constructed for municipal wastewater treatment study at NRA, Norway. The pilot plant constitutes of a pre-denitrification (R1), two aerobic CFIC stages (R2 and R3), and a sludge settler for sludge removal and supernatant return to biological stages (**Figure 7**). The three biological stages are 8.7, 8.3, and 8.3 m^3, respectively, in volume. Biocarriers of BWT15® and BWTX® (**Figure 3**) were filled in the first and the other two stages separately. During normal CFIC operation, a filling ratio of 62, 86, and 83%, respectively, is applied. The filling degree of the pre-denitrification was kept constant at 62% while reduced to 71 and 69% when intermittent washing cycle was performed in the other two aerobic stages.

The pilot was fed with municipal wastewater directly pumped from the full-scale primary clarifier onsite (**Figure 7**), and the wastewater characteristics are given in **Table 2**. The wastewater temperature was around 15°C in the whole year. The wastewater was fed at 3–6 m^3/h to the system with a recycle ratio of 1–1.5 during the study. To facilitate biofilm growth on carriers, washing mode was applied at the beginning of the test until stable biofilm growth was observed. The pre-denitrification stage was washed daily, and the two aerobic stages were washed together in every 1 or 2 days after the first reactor washing cycle finished. The washing cycle for each stage

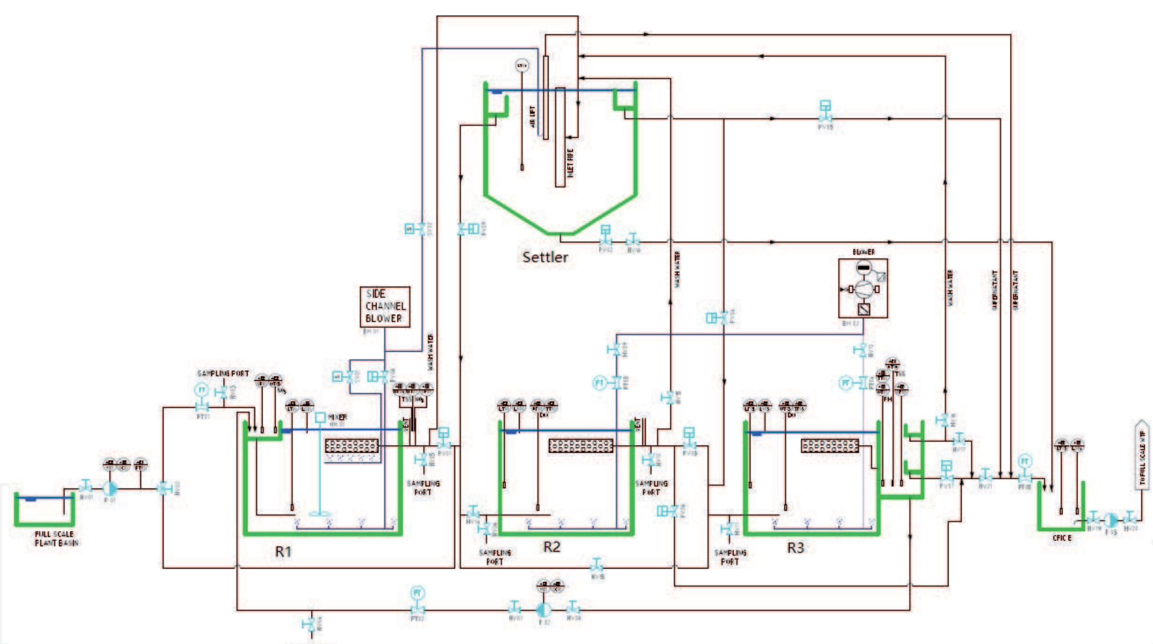

Figure 7.
Pilot system PID layout.

Average feed condition	Period 1 (15.05–29.06)	Period 2 (24.10–01.12)
TCOD (mg/L)	392	214
TSS (mg/L)	264	123
NH_4-N (mg/L)	20.4	14.5
TN (mg/L)	45	29
pH	7.2	7.0

Table 2.
Feed wastewater characteristics in the two test periods.

is normally 1 h. Wastewater samples were taken for analysis before and in the washing cycle to record parameters such as COD and suspended solid.

3.2 COD and ammonium removal

Pilot performance in period 1 (**Table 2**) is presented below. Feed wastewater characteristics show that during this period more than 80% of the feed COD was particles. The influent total COD was mostly removed/retained in the denitrification reactor (R1), and the effluent TCOD in R2 and R3 is identical (**Figure 8**). Soluble COD removal was about 30%, with 16% removed in R1 and the rest was removed after R3. The feed ammonium concentration was around 20 mg/L (**Figure 9**) after combining with recycle wastewater from R3, the ammonium content was diluted to about half of initial value, and it can be seen that significant NH_4-N is removed in the first (80%) aerobic reactor (R2) (**Figure 9**) to an average concentration of 1.5 mg/L. After aerobic stage 2, the NH_4-N concentration was on average 0.6 mg/L. Due to very low available organic for denitrification (C to NOx-N ratio of on average 1.7), the total nitrogen removal was about 36%. Limited flow capacity of the pilot giving the TN and NH_4-N loading rate about 0.4 g N/m_2/d, which was much lower than previously tested (>2 g N/m^2/d in a small-scale reactor).

3.3 Solid removal

Comparing to a traditional MBBR, CFIC process has good capacity to retain particles inside the carrier filter bed (instead of being continuously washed out of the system in conventional MBBR). The pilot study shows that during the MBBR mode (CFIC washing), the total suspended solid (TSS) content in the three stages was similar at around 250 mg/L, which was slightly lower than the feed TSS of about 300–400 mg/L. While in the CFIC normal operation model, the TSS was lower than 100 mg/L in all three stages with an average value of 50 mg/L. This is five times lower than a MBBR effluent TSS content, which indicates that solids were retained in the CFIC process.

CFIC washing cycle can normally bring out a large quantity of solid attached or accumulated in a short period. The average solid content for the washing water

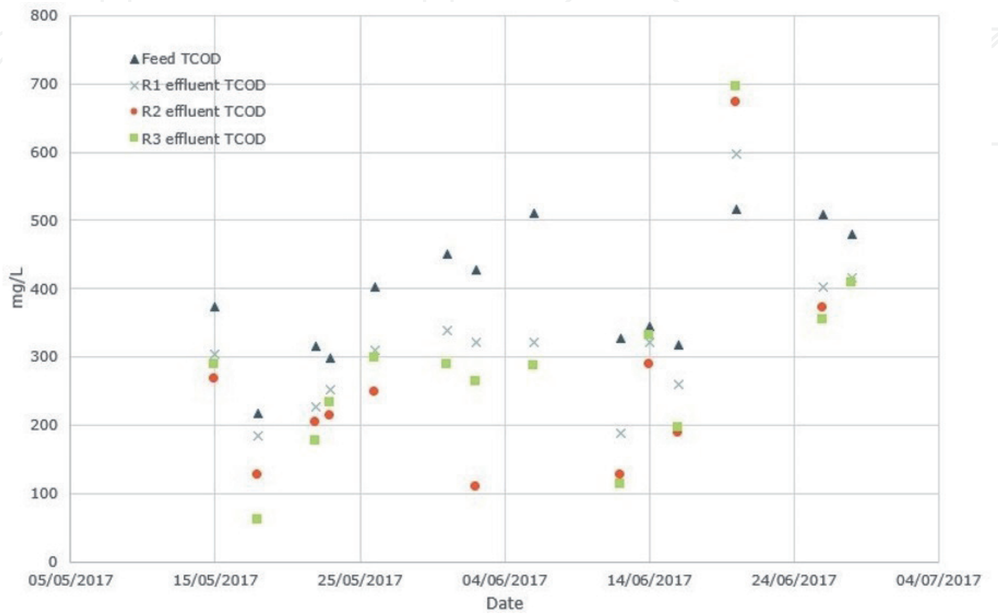

Figure 8.
COD removal by the CFIC pilot, R1, pre-denitrification; R2 aerobic stage 1 and R3, aerobic stage 2.

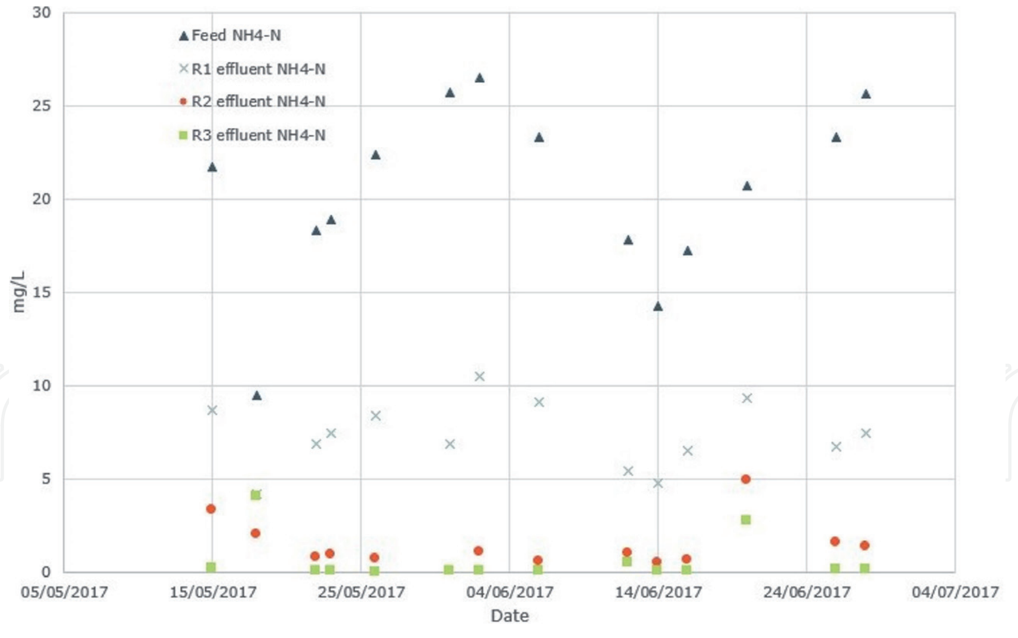

Figure 9.
NH_4-N removal by the CFIC pilot, R1, pre-denitrification; R2 aerobic stage 1 and R3, aerobic stage 2.

is 1.3–6.4 times of the influent wastewater TSS in this study depending on washing frequency and accumulation of solids. The washed-out sludge has low sludge volume index (SVI) of around 70 mg/L and can settle quickly in a fast sludge settler. This feature enables at least two times smaller clarifier for sludge settlement comparing to the one needed for conventional MBBR processes. The solids washed out of the system can be from 3 to 12 g TSS/m^2 carrier surface, accounting for 3–14% of the total attached TSS [36]. The washing water peak TSS content can reach over 2000 mg/L and gradually reduced with continuous wastewater feeding after washing stops [36, 37]. Over 50% of the washed-out particles are larger than 60 μm, which is larger than normal influent and effluent values [36], explaining the low SVI level. It may take 1–4 h until the effluent solid content reaches a stable condition after each washing.

4. Conclusions

Wastewater treatment by applying biofilm has been developed over the years, and various biofilm processes are playing important roles at different stages of wastewater treatment industries. MBBR concept based on biofilm is widely used for organic and inorganic removal in both industrial and municipal wastewater remediation. It is approved to be a compact, energy-efficient, and robust solution comparing to a traditional activated sludge process. Due to biofilm growth on a protected area, different organism species coexist in the MBBR biofilm clusters which enhances their resilience to the environmental condition variations. The development based on MBBR to even compact process such as CFIC and HyVAB and the integration of MBBR with other high-rate and efficient processes could potentially reduce the footprint and complexity of wastewater treatment. Future studies to improve MBBR system for high mineral content wastewater treatment, optimize carrier designs and understand the correlation between protected area and organism species in different environmental condition, the biofilm growth, and detachment mechanisms induced by external forces and improving the energy efficiency for enhanced mass transfer are interesting topics to be explored.

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