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Article

Comprehensive Review of Industrial Wastewater Treatment Using Sponge Moving Bed Biofilm Reactor

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Abstract: For treating industrial wastewater, the technology of Moving Bed Biofilm Reactor (MBBR) has proven to be a highly effective and environmentally friendly option. With an emphasis on sponge-based carriers, this review thoroughly investigates the fundamentals, uses, benefits, and drawbacks of MBBR systems. To increase microbial activity and the effectiveness of pollutant removal, MBBR integrates attached and suspended growth processes and makes use of free-floating biofilm carriers. Compact design, high treatment capacity, operating flexibility, and little sludge output are some of the main advantages. The research emphasizes the effects of several carrier materials on system performance, including polypropylene and polyurethane sponge. A variety of MBBR process designs for the removal of nutrients and organic matters are also covered, along with case studies showing effective implementations in various industries. Notwithstanding its benefits, issues including carrier congestion and the requirement for more study on hybrid systems are mentioned. According to the review's findings, MBBR technology, especially when combined with sponge carriers, offers an economical, scalable, and ecologically benign method of treating wastewater, making it appropriate for large-scale.

Keywords: MBBR, wastewater treatment, biofilm carriers, sponge media, industrial effluents, sustainability

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1. Introduction

The past few years have witnessed considerable consequences to water resources due to industrialization. Virtually all forms of industry utilize water as a significant industrial resource, and therefore, they produce great amounts of wastewater and effluents which are extremely detrimental to the biosphere. Today, the greatest challenge which has claimed the attention of scientists is developing an efficient and sustainable approach with which to manage the industrial wastes and biowastes using ecosystem-friendly methods. Biodegradation, for example, is gaining more and more attention due to its eco-friendly nature. Nevertheless, the presence of stubborn recalcitrant compounds in wastewater still makes it difficult to utilize on a broad scale. Now, the moving bed biofilm system appears to be highly promising in terms of its capability to treat a wide range of types of industrial wastewater pollutants. The purpose is to present the moving-bed biofilm systems concerning their application for the treatment of different industrial wastewaters, analyzing their overall merits and shortcomings, subjecting them to thorough critical assessment along recent research activities in the field, and evaluating the sustainability of biofilm systems for large scale implementation [1]. One of the newer technologies that can meet these requirements is the moving bed biofilm reactor (MBBR). By combining suspended growth and attached growth processes, MBBR has demonstrated its high removal efficiency and dependability as a biological technique for the removal of carbon and nitrogen [2], [3]. The MBBR system has numerous benefits by incorporating free floating biofilm carriers into the aeration tank, including a large surface area for colonization, high specific biomass activity, minimal space requirements, easy construction, and low sludge formation that improves oxygen transmission [4], [5], [6], [7]. Within the MBBR framework, the Biofilm carriers seriously influence the overall efficacy and performance of wastewater treatment [5], [8].

2. Materials and Methods

This study employed a qualitative systematic review methodology to comprehensively examine the application of the Moving Bed Biofilm Reactor (MBBR), with particular emphasis on sponge-based carriers, in industrial wastewater treatment. The methodology was designed to synthesize existing theoretical and empirical knowledge rather than generate new experimental data. A structured literature review approach was adopted, whereby peer-reviewed journal articles, review papers, technical reports, and case studies related to MBBR technology were collected from reputable scientific databases and publishers. The selection criteria focused on studies addressing reactor configuration, carrier materials, biofilm behavior, pollutant removal efficiency, and operational performance in industrial and municipal wastewater treatment contexts. Special attention was given to studies investigating sponge and polyurethane-based carriers due to their high porosity and microbial immobilization capacity. The collected literature was critically analyzed to compare different MBBR designs, carrier types, filling ratios, and process alternatives, including aerobic, anoxic, and hybrid systems. Data from previous experimental results and full-scale applications were qualitatively assessed to identify performance trends, advantages, and technical limitations of MBBR systems. In addition, historical development and technological evolution of MBBR processes were reviewed to provide contextual understanding of their scalability and sustainability. The analysis also incorporated comparative evaluation with conventional biological treatment methods to highlight the relative effectiveness of MBBR technology. The findings were synthesized thematically, focusing on system efficiency, operational flexibility, space requirements, and environmental sustainability. This methodological approach ensured a comprehensive and integrated assessment of MBBR technology as a viable solution for industrial wastewater treatment, while identifying existing research gaps and directions for future investigation.

3. Results and Discussion

Moving Bed Biofilm reactor (MBBR).

The MBBR was created as one of the wastewater treatment methods in the 1980s by Hallvard Degaard, a professor at the university of Norway the techniques and Science [9]. This method was developed in response to the requirement for more compact wastewater treatment procedures that have a high capacity for organic matter removal [10], [11].

MBBR use carriers that are made to provide the biomass with a protective surface and the best possible environment for the growth of microorganisms while they are floating freely in the reactor's water. Microorganisms may have more places to grow and absorb if the carrier surface area is bigger [12]. MBBR function continuously, much like activated sludge, but with the addition of microscopic carrier components. These carriers are composed of polypropylene, a plastic, and have a low density (just about 1.0 g/cm^3). They so go through the reactor together with the water. Figure 1 shows a typical MBBR media carrier.

Figure 1. Typical MBBR media carriers [11]

ADVANTAGES OF MBBR Media

Using the MBBR media technology in the facilities of wastewater treatment has several advantages. These benefits make MBBR medium a potent substitute for conventional procedures such as membrane bioreactors and activated sludge [13].

1. Efficiency of space

The same wastewater volume that processes like activated sludge and trickling filters require enormous tanks to treat can be treated with a modest amount of MBBR. There will be more room in your facilities for additional equipment.

2. Ease of use

Even novice personnel can easily operate biofilm reactors. Wastewater flow rate, surface area loading rate (SALR), biological oxygen demand (BOD), and nitrate or ammonia concentration variations are all naturally adjusted for by the system. After calculating the MBBR system's design.

3. Infrequent maintenance:

MBBR systems require little upkeep and run on their own. By allowing for continuous movement within the tank, aeration grids help avoid media blockages. Additionally, the device automatically adjusts its levels of producing biofilm to an ideal pace.

3. Load flexibility:

MBBR systems can withstand disturbances thanks to fixed film and suspended growth biological processes. When managing shock loads or abrupt changes in chemical composition, this flexibility offers stability.

4. Rapid hydraulic retention:

Because of a short hydraulic retention time (HRT), facilities will be able to treat more water every day after converting from other media. Because of the media's continuous action, MBBR processes liquids more quickly, enhancing your water treatment capabilities.

MBBRs' attached-growth carriers

The composition of material, form, specific surface area, and treatment abilities of moving bed connected growth carriers vary greatly [14]. Moving bed carriers made of plastic are the most common and original type (Figure 2). These tiny, cylinder-shaped polyethylene carriers have a grooved exterior and a cruciform internal support [15]. Typically, the carrier filling ratio falls between 40 and 70 percent. At the typical filling ratio of 67%, the carriers' potential attached- growth area is roughly 465 m^2m^{-3} [16]. An estimated 350 m^2 m^{-3} is the effective attached-growth area [15].

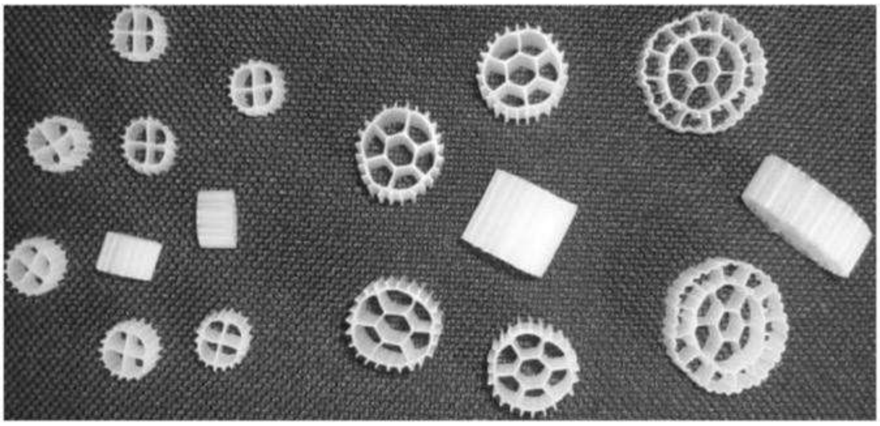

Figure 2. Biofilm carriers of Kaldnes types K1, K2 and K3

Some wastewater researchers have reported using polyurethane foam sponge for immobilizing microorganisms (Figure 3) [17]. Cell counts in the sponge range from 45 to 90 cells per 25 mm, making it a very porous substance. Polyurethane foam is often chopped into tiny cubes to create the carriers. According to earlier research, the usual filling ratios were 10% and 20% [17], [18]. When membrane-coupled MBBRs are applied, the polyurethane foam has been shown to have the ability to lessen layers of cake that form on the membrane's surface in addition to provide support for attached growth [17].

Figure 3. Cubes of Polyurethane sponge with attached-growth biomass

Alternatives to the MBBR Process

There are numerous applications for the highly adaptable MBBR wastewater treatment method. The following six MBBR process alternatives will be described and discussed:

1. One-step BOD elimination
2. Tertiary Nitrification in a single step
3. Removal of BOD in two stages
4. Nitrification and BOD removal in two stages
5. Nitrification/Denitrification/Pre-Anoxic BOD removal
6. Nitrification, denitrification, and elimination of post-anoxic BOD

The diagram below Figure (4) displays the flow diagrams for these six MBBR process variants.

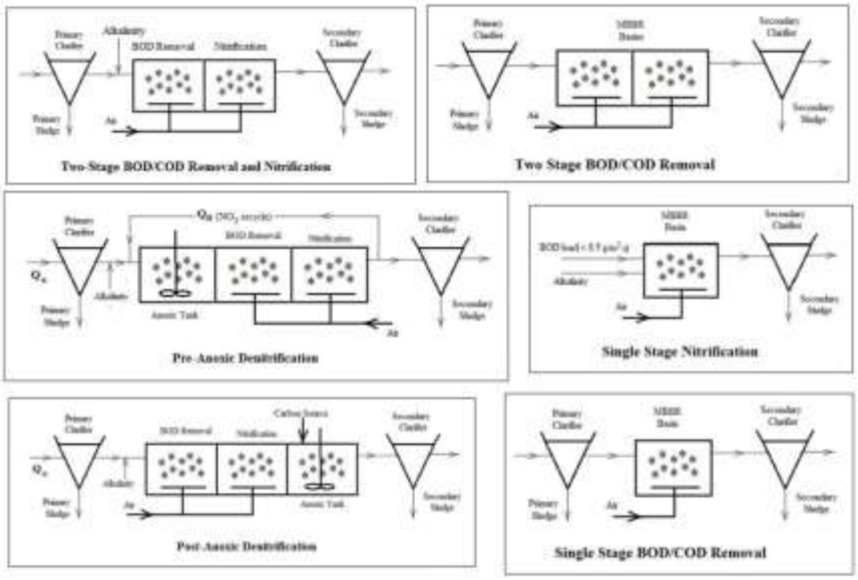

Figure 4. MBBR Wastewater Treatment Process Alternatives [Bengtson]

Overview of MBBR Process

The business developed the MBBR procedure in was the late eighteenth century, Anox Kaldnes in Norway, in collaboration with the Water Treatment. After being patented, this novel method was dubbed the Kaldnes of Moving Bed Biofilm process.

Odegaard 1999**,** Rodgers and Zhan 2003, The first MBBR facility opened for business in Norway, in 1990. Weiss. 2005, After doing some pilot-scale research, the Norwegian Dairies Association recommended that the purpose of this novel MBBR be was treated dairy waste. Rusten 1992, Moving bed biofilm reactors have become increasingly appealing and well-liked due to their cost-effective design and technological innovations. According to, in 2006, Rusten , Kermani 2008, Zafarzadeh 2010 and Koupaie 2011 there were over 400 operational MBBR-equipped wastewater treatment facilities in 22 different countries up to the year 2006. Veolia kept the developed biocarriers' original names after acquiring the Anox Kaldnes in 2007. In 2014 According to Biswas et al., there were 1200 operational MBBR plants spread across over 50 nations in 2014 [19], [20], [21], [22], [23], [24], [25], [26], [27].

By merging best features of biofilter and activated sludge process without moving bed biofilm process which integrates the worst is essentially a modified one of the two forms. Utilizing a suitable sifting system at the reactor's output

The biomass is cultivated on biocarriers, which are freely moving carriers that are placed within the reactor. While the biocarriers can be found in the most popular are small, hollow plastic cylinders in a variety of shapes. These tiny biocarriers made of polyethylene with a high density of 0.95 to 0.98

The biofilm in the reactor grows at g/cm3. The agitation that resulted helps the biofilm carrier move during the aeration process but biofilm is mechanically moved by agitator carrier in processes that are anoxic and anaerobic processes, as illustrated in (Fig.5) Increased volumetric treatment capacity, reduced carrier medium clogging, and less head loss are some benefits of the MBBR technology almost activated the sludge, moving bed biofilm system's reactor contains the entire operational tank size for biomass production. Unlike other sludges that are activated, Biofilm reactors do not require sludge recycling, which reduces the difficulty of getting rid of extra biomass. The ability to determine the volume of media carrier should employ based on the treatment's requirements and quantity. As a result, the precise biofilm area can be changed appropriately. Nonetheless, it is advised that the number of carriers employed be 67% of the reactor's overall capacity, and in any event, not greater than 70%. For example, when the 70% filling criterion is used, the film's potential growth area is 500 m2/m3, and as biofilm formation occurs inside the carrier, The particular surface on which biofilms grow will be around 350 m2/m3.

Odegaard, 2006. As the fixed biomass concentrations can range from 10,000 to 12,000 mg/l. About 3 to 4 kg SS/m3 is the MBBR, which is equivalent to activated sludge. The moving bed process's volumetric removal rate is sufficiently high due to the high biomass concentration, making it a significantly more viable process than other similar systems Odegaard 1999. Moving bed biofilm reactor operating principle in aerobic and anoxic process is depicted in Figure 1. The evolution of MBBR technology over the last 20 years has been praised for its ease of use, durability, adaptability, and compact size in wastewater treatment Weiss 2005, Jenkins and Sanders 2012 [21], [28].

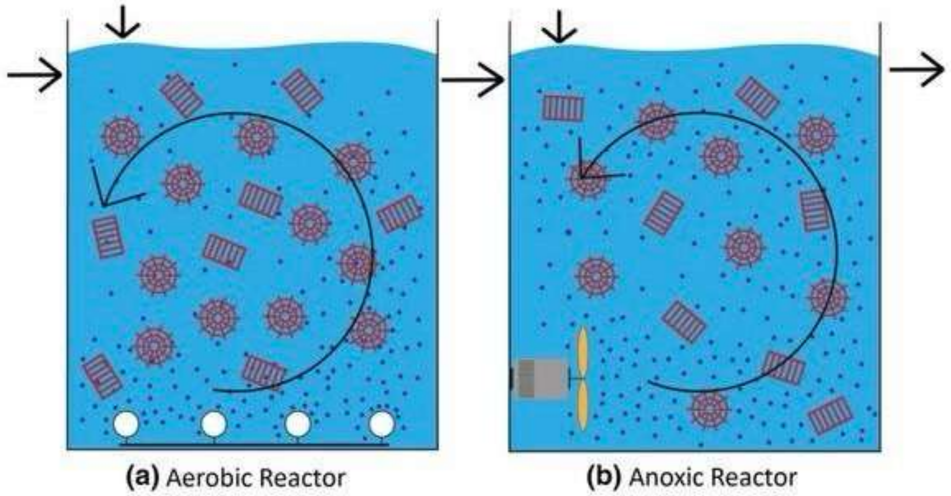

Figure 5. The moving bed biofilm reactor operation in aerobic and anoxic processes

The method shows great promise in lowering the pollutant load and contamination, outperforming Das and Naga's surface aeration system 2011[29] Because of the system's reliability and simplicity of use MBBRs prove to be among the greatest options and an incredible alternative used in the treatment of many different kinds of wastewater. Additionally, improvements in operation and design lead to smaller footprints, which significantly reduces the production of suspended solids and produces higher-quality reusable water, which in turn reduces the amount of waste that must be disposed of Several researchers' investigations showed that MBBR technology has been effective in both industrial and municipal wastewater, including pulp and pharmaceutical wastewater paper and laundry. Biswas 2020, Bering 2018 , Vaidhegi 2013, Brinkley 2007 , Santos 2020, Singh 2018 Additionally the system is beneficial drinking water denitrification as well as other surface water operations.
McQuarrie and Boltz (2011), Kermani et al. (2008). Numerous studies demonstrated that MBBR enhances the technology used for treatment for wastewater from cities and industries [25], [30], [31], [32], [33], [34], [35]. The system of MBBR has a high to an activated sludge system. Goswami and Mazumdar for tanneries As stated by Erkan et al saw textile wastewater reach an efficiency of 98.5% there are numerous MBBR forms that have been established in therapy [36]. various regions of the world as a result of different carriers that are utilized to develop biofilms with the same fundamental idea. Among the well-known are LINPOR, Captor Among them are PEGASUS. According to Morper's 1994 assignment; Gilligan and Morper 1999 [37], [38]: The German-developed LINPOR process uses highly cubes of porous plastic foam that transport biofilms. This was suspended
When combined with freely suspended biomass, porous media provides a significantly higher concentration of total biomass, enabling the system to function at higher speeds.
is a sophisticated method that promotes nitrification and includes
Microorganisms are immobilized on nitrifying pellets called Bio-N
polyethylene glycol cubes. Its residence time is only 6 to 8 hours.
and is readily adaptable to the current tank size, In 2018, Benakova et al.

Dezotti et al. , systems [39], [40]. These days, the current treatment plants must be upgraded with stumpy extra expenses to increase the capacity for treatment because of the increasing in population. Additionally, it is imperative to seek treatment. that reduce the strain on the environment because of simple installation and operation by taking up little space [41], [42], [43], [44].

4. Conclusion

The MBBR , or Moving Bed Biofilm Reactor has proven to be a robust and adaptable technology for industrial wastewater treatment. With its high ability to remove organic pollutant, ammonia, and fat, it is very suitable for treating the specific challenges posed by industrial effluents. Space-saving in nature and relatively easy to manage, MBBR systems are resistant to toxic shocks and load variations typical of this industry.

New technologiesi.e., enhanced biocarriers, intelligent automation, hybrid hybrids, and energy-saving aeration have greatly improved MBBR performance at lower operating cost. These technologies further improve the attractiveness of MBBRs for full-scale application, particularly in cases with space constraints or variable influent conditions.

However, all such problems like high initial cost, carrier fouling, and biofilm detachment need to be addressed. Constant research and technological progress need to be used for solving these drawbacks and making the system scalable and more reliable.

In the coming years, application of MBBRs in enabling sustainable wastewater treatment will only increase. From being integrated with renewable power plants to modular application for decentralized treatment, MBBRs present a future-proof and sustainable choice. Efforts needed only when provided with perfect conditions throughout and with regular innovation, MBBRs will continue to contribute as a vital technology in addressing the increasing needs of industrial wastewater treatment

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