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Review Article

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Bacterial community dynamics and pollutant removal mechanisms in biofilters: A literature review

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Abstract

Background: The lack of understanding of how pollutant removal occurs in biofilter reactors and bacterial community dynamics makes this worthy of study. This review explores biofiltration processes, commonly used biofilter types, bacterial community dynamics, and pollutant removal mechanisms in biofilters.

Methods: This review used data from previous studies published on Scopus, EBSCO, and ProQuest, categorized into parameters such as the biofiltration process, types of biofilters, bacterial community dynamics, and pollutant removal mechanisms. The data were narrated, analyzed in a table, and presented in a review.

Results: In the biofilter reactor, microorganisms cover the medium, allowing pollutants to flow through gaps and contact the biofilm layer. As the biofilm thickens, adhesion weakens, leading to new colonies. Submerged-bed biofilters, trickling filters, and packed column aeration and gasification systems effectively remove nutrients from aquatic environments. Biofilter bacterial communities are categorized by filter layer depth, with fast-growing, less specialized communities in the upper layer and more specialized communities in the bottom layer. Pollutant biodegradation depends on various factors such as nutrient availability, oxygen concentration, pH, bioavailability of contaminants, and physical and chemical characteristics of the biomass.

Conclusion: A biofilter reactor uses microorganisms to cover a medium, allowing pollutants to flow through gaps and contact a biofilm layer that degrades organic compounds. Submerged-bed biofilters, trickling filters, and packed column aeration systems can effectively remove pollutants. Biofilter bacterial communities are categorized by filter layer depth, with fast-growing, less specialized communities in the upper layer, and more specialized communities in the bottom layer.

Keywords: Wastewater, Bacteria, Biofilms, Environmental pollutants, Nutrients

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Introduction

Wastewater contains various dangerous contaminants including organic matter, nitrogen, phosphorus, and pathogens (bacteria and viruses) (1,2). Physical, chemical, and biological pollutants degrade many properties of water after they are introduced. The physical characteristics of water include suspended solids, total dissolved solids, and electrical conductivity (EC). The composition of different minerals, carbon concentrations, dissolved oxygen, nitrogen, and phosphorus determine the chemical properties of a substance. The term "biological property" describes the existence of different types of bacteria, viruses, algae, protozoa, nematodes, insects, and their progenies (3).

Technological advances in biofiltration can provide practical solutions for these issues (4,5). A combination of biological oxidation, adsorption, and filtration processes influences pollutant elimination during biofiltration (6). Solid materials are used as matrices in the biofiltration process, where microorganisms that break down contaminants proliferate biologically (7). Particles of activated carbon, gravel, sand, and plastics can be found in the matrix (8,9). Microorganisms proliferate and change continuously in response to nutrient availability. Eventually, they cover the surface of the media and produce a thin layer of biomass known as a biofilm (10,11).

The use of a group of chemoautotrophic bacteria and archaea in an oxic environment to oxidize nitrogenous wastes from cultured specimens and related organic inputs to colonies is known as biological filtering (12,13). Many organic and inorganic contaminants have been effectively removed by biofiltration processes, including those that are considered relatively hazardous, poisonous, and rarely biodegradable (14). Achieving the required degree of pollution removal efficiency largely depends on the properties of the solid material employed as the filter media. Material type, shape, size, surface area, porosity, and surface roughness affect the effectiveness of the filter medium (15,16). Owing to its widespread availability, quartz sand is a potential biofilter medium for water treatment. Because the grains of quartz sand are tiny and have stable characteristics, there is a small void between the particles and a large contact surface area in the biofilm (17,18). As a result, there will be more interactions between the biofilm and contaminants in raw water. This situation is ideal for increasing the effectiveness of pollutant removal through biofiltration (19,20).

To meet the growing demand for safe and high-quality drinking water, biofiltration treatment is gaining attention globally. These benefits include avoiding the addition of chemicals, low energy input, and higher removal efficiency in terms of turbidity, organic compounds, undesirable tastes and odors, and pathogens (e.g., bacteria, viruses, and protozoa) (21,22). Biofiltration is a technique that, unlike other conventional filters, not only uses physical and chemical methods (such as sorption and straining) to remove tiny particles but also, uses biological processes to absorb and break down contaminants (23,24). Since the early 1900s, it has been utilized in Europe to clean surface water to successfully lower turbidity and cholera bacteria in drinking water applications. However, it was shown to be beneficial in lowering microbial growth (in distribution pipelines), corrosion potential, and disinfection byproducts, and the significance of biofiltration in drinking water treatment became apparent (25).

There is a research gap that has not been widely studied by other researchers regarding the combination of biofiltration processes, commonly used biofilter types, bacterial community dynamics, and pollutant removal mechanisms in biofilters in a structured manner in one understanding. Therefore, it is necessary to conduct studies to provide information on the topic being studied. The information obtained will be very useful for the development of an effective and efficient biofiltration system, the development of bacterial community dynamics in biofilters, and ways to improve pollutant removal in biofiltration systems with modifications that can be made based on this review article.

Here, we review bacterial community dynamics and pollutant removal mechanisms in biofilters. We aimed to explore the biofiltration processes, commonly used biofilter types, bacterial community dynamics, and pollutant removal mechanisms in biofilters. We hope that this review will provide a clear picture of future research on the development of biofilters for more efficient and environmentally friendly wastewater treatment. With a deeper understanding of bacterial community dynamics and pollutant removal mechanisms in biofilters, innovative solutions can be found to improve the performance of wastewater treatment systems.

Materials and Methods

Supporting data for this review were obtained from articles published by previous research on reputable sources, such as Scopus, ProQuest, and EBSCO. For data on biofiltration processes, commonly used biofilter types, and pollutant removal mechanisms in biofilters, we considered the time range between 2014 and 2024. However, we did not find any recent studies on bacterial community dynamics. Therefore, we did not limit the publication time of the articles included in this review. Keywords for the search process included biofiltration processes, biofilter types, pollutant removal, bacterial community, and similar words appearing in each database's filters. The data obtained were then synthesized based on the needs of the review by dividing it into several parameters according to research objectives, such as the biofiltration process, types of biofilters, dynamics of the bacterial community in the biofilter, and pollutant removal mechanisms that occur in the biofiltration process. The data that have been separated based on the parameters are then narrated in the articles and included in the results and discussions, presented in figures and tables. Researchers have provided relevant theories to support and strengthen the results and discussions.

Results

This review explored biofiltration processes, commonly used biofilter types in wastewater treatment, bacterial community dynamics, and pollutant removal mechanisms of biofilters.

Biofiltration processes

In a biofilter reactor, microorganisms cover the entire surface of the medium. During operation, water containing pollutant compounds flows through the media gaps and comes in direct contact with the microbial mass layer (biofilm) (26,27). Biofilms formed in the top layer of the media are called zoogleal films and consist of bacteria, fungi, algae, and protozoa (28). Bacterial cells play the most important role and are widely used in wastewater treatment processes. Therefore, the cell structure of other microorganisms can be considered the same as that of bacteria (29,30). The process that occurs during the formation of biofilms in wastewater is the same as that occurring in the natural environment. Microorganisms in biofilms degrade organic compounds in the water (31,32). A thicker biofilm layer results in reduced oxygen diffusion to the underlying biofilm layer, which creates an anaerobic environment in the upper biofilm layer (33).

The growth of microorganisms continues in the formed slime, which increases the thickness of the slime (34,35). The diffusion of food and O^2 occurs at the maximum thickness. Under these conditions, food and O^2 are no longer able to reach the solid surface or the furthest part of the liquid phase. This causes the biomass layer to be divided into two parts: the aerobic and anaerobic layers. If the biofilm layer becomes thicker, the adhesion of microorganisms to the supporting medium will not be sufficiently strong to withstand the gravity of the biofilm layer and the biomass layer will peel off (36,37). New colonies of microorganisms form a biofilm layer on peeled surfaces (38). Peeling can also occur because of the excessive erosion of the fluid flowing through the biofilm. In the aerobic process, the efficiency decreases with increasing maximum layers and increasing anaerobic layer thickness (39). Even though the biomass layer is several millimeters thick, only the outer layer with 0.05-0.15 mm thick is the aerobic layer (40).

Biofilm formation begins with the attachment of bacteria to the surface, followed by the secretion of extracellular polymeric substances that create a protective matrix. This matrix allows bacteria to adhere and form a structured community that is resistant to antimicrobial agents. As the biofilm matures, more bacteria join the community and continue to produce extracellular polymeric substances, further strengthening its structure. This complex network of bacteria provides a safe environment for microorganisms to thrive and communicate with each other, thereby enhancing their survival capabilities. The following section explains how biofilms can form (Figure 1).

Commonly used biofilter types in wastewater treatment

Several types of biofilters are commonly used in the biofiltration process with various modification techniques, including biofilters with submerged beds, trickling filters, and rotating disks. The form and explanation are shown in Figures 2, 3, and 4.

Dynamics of bacterial communities in biofilter

A biofiltration reactor contains a medium in which bacteria can proliferate and aid in the removal of pollutants. In summary, contaminants found in liquid waste are broken down by microorganisms present in the media. When grown on media, microorganisms break down and form biofilms. Superior media have a high surface area, pollutant homogeneity, and water retention for biofilm survival. Under these conditions, microorganisms reduce the amount of liquid waste pollutants. The bacteria listed in Table 1 are commonly detected in biofilter reactors with their respective roles in the reactor. These bacteria

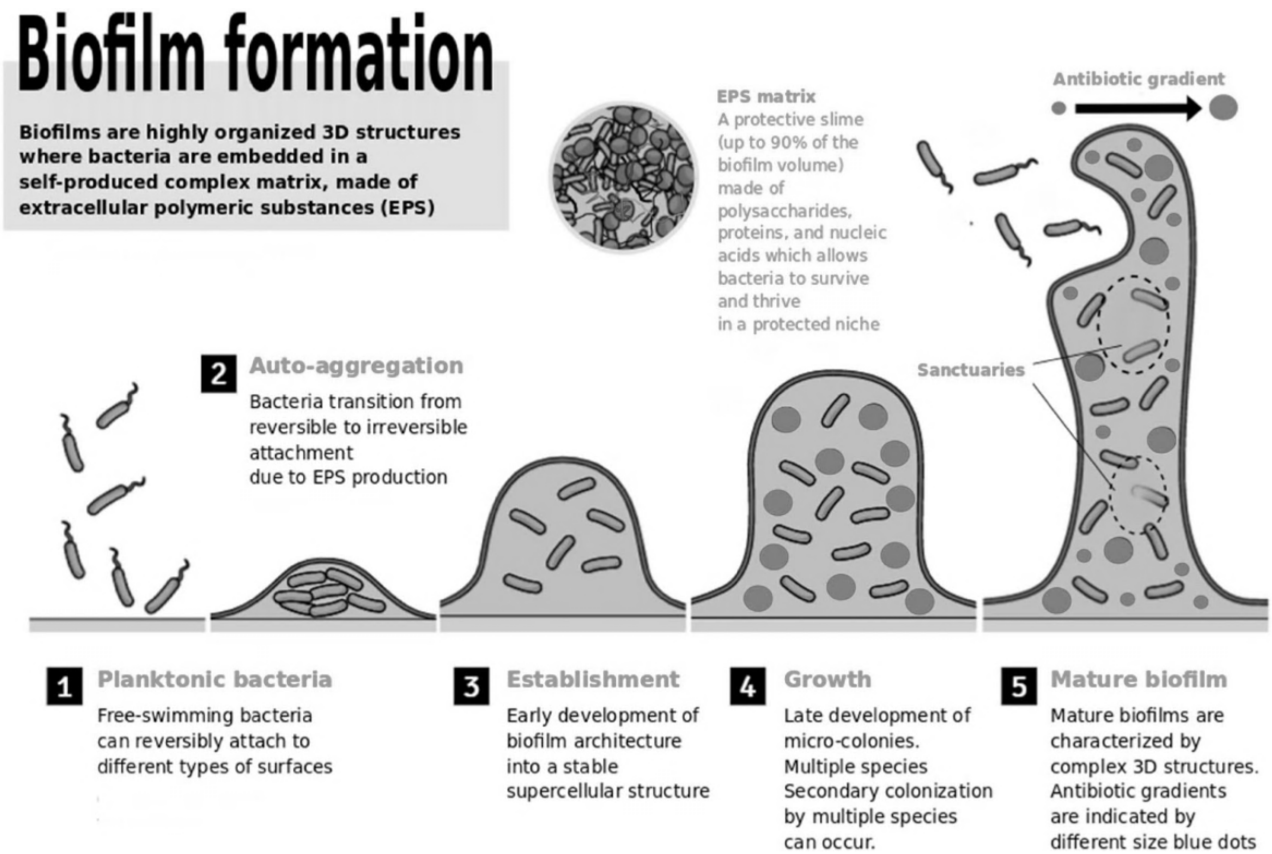

Figure 1. Biofilm formation mechanism. Reproduced under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/) (41)

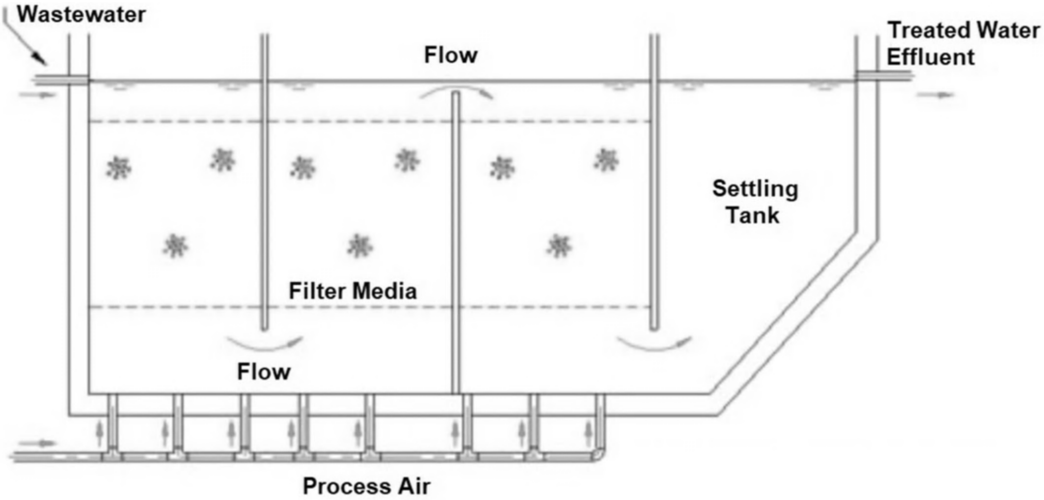

Figure 2. Submerged-bed biofilter. Reproduced under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/) (42)

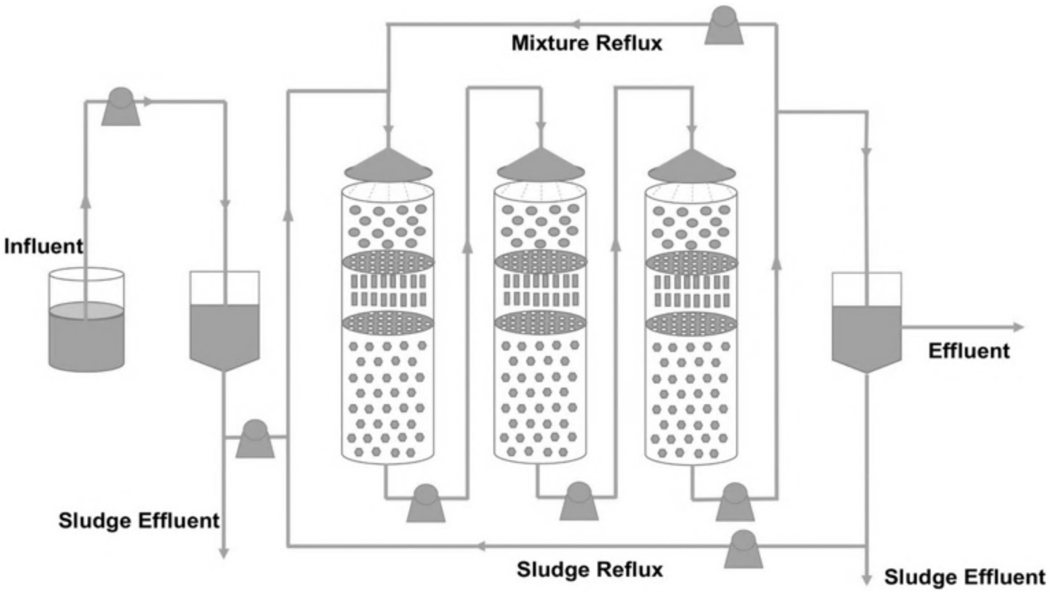

Figure 3. Trickling biofilter. Reproduced under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/) (43)

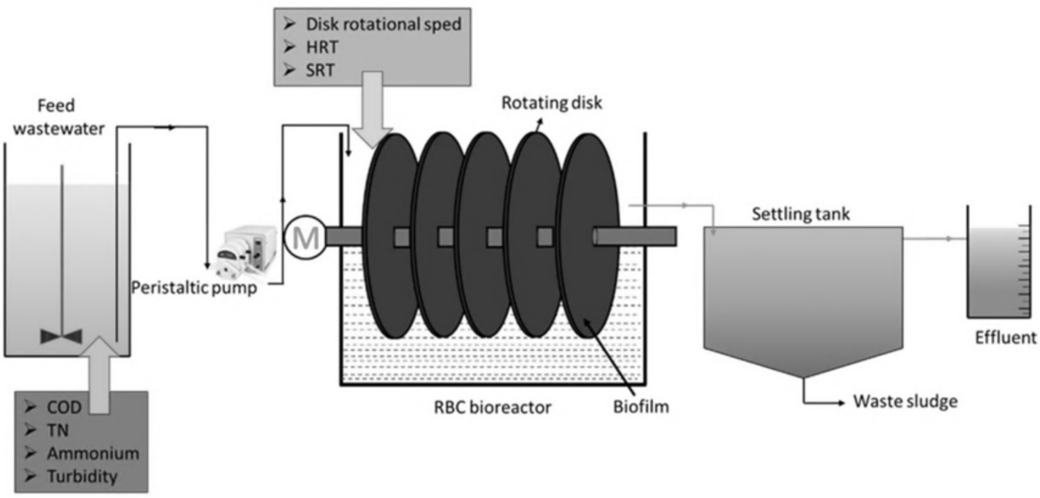

Figure 4. Rotating-disk biofilter (rotating biological contactor). Reproduced under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/) (44)

are found in various conditions and locations. They have been found in wastewater samples, biotrickling filters, and biofilms. Consequently, wastewater processing techniques have been developed to eliminate both organic matter and heavy metals. The additional details are provided in Table 1.

Contaminant removal mechanisms

The biofilter process for removing pollutants depends on the type and age of the filter medium(62). For non-porous media such as sand, filtration, and biodegradation are the main mechanisms. Porous media is involved in biofilm absorption and biodegradation by microorganisms. This combination allows for the effective removal of a wide range of contaminants, making biofiltration a sustainable and environmentally friendly processing option (63).

Biofilms are essential to aquatic ecosystems as they provide habitats for microorganisms that feed on pollutants and decomposing organic compounds. They protect microorganisms from harsh environmental conditions and play an important role in nutrient cycling, thereby affecting the ecosystem's health (64). Dissolved organic matter, which is the primary substrate in drinking water and wastewater biofilters, releases nutrients for ecosystem productivity (62).

Pollutants are removed via secondary substrates or co-metabolism, thereby maintaining the balance of aquatic ecosystems. Biofilms contribute to the natural degradation of pollutants and support diverse microbial communities (65). Pollutant biodegradation depends on factors such as nutrient availability, oxygen concentration, pH, and biomass characteristics. Bioregeneration, in which the biofilm renews adsorption sites through microbial activity, helps remove pollutants from the filter, resulting in increased system stability and a longer activated carbon lifetime (66).

Table 1. Bacteria types found in the biofilter reactor

Bacteria	References
Proteobacteria, Bacteroidetes, and *Actinobacteria*	(45-47)
Comamonadacea	(46)
Comamonas testosteroni	(48)
Burkholderiales	(49)
Flavobacteriaceae, Alcaligenaceae, Cytophagaceae, Cryomorphaceae, Piscirickettsiaceae, and *Trueperaceae*	(50)
Comamonas nitrativorans	(51)
Proteobacteria, Bacteroidetes, and Actinobacteria	(52)
Rhodospirillum sp	(53)
Azolla	(54)
Gallionella ferruginea, Leptothrix sp.	(55)
Eichhornia crassipes	(56)
Desulfovibrio sp.	(57)
Gracilaria sp.	(58)
Thauera selenatis	(59)
Thiomonas sp.	(60)
Sargassum filipendula	(61)

Other studies have shown that compared to combination biofilters, single biofilters are more effective in removing color and chromium. This means that a biofilter system that uses one medium is better than one that uses several media, especially sawdust and pozzolan. However, combination media can effectively remove chemical oxygen demand (COD) compared with single media (67).

During the bioregeneration process, exoenzymes released by bacteria penetrate the activated carbon pores and interact with the substrate. This reduces the absorption capacity, allowing metabolites to be absorbed, and substrates or enzymes to undergo hydrolytic breakdown. Bioregeneration increases the system stability and lifetime of activated carbon. The factors that influence bioregeneration include substrate absorption capacity, microorganisms, environmental conditions, and optimal microbial growth (32)

A brief description of the pollutant removal process in the biofilter reactor is depicted in Figure 5.

Discussion

Biofilter process in domestic waste processing

In the biofilter process, microorganisms will develop and grow in the buffer media used. Various media can be used as a place for microorganisms to attach or grow, such as media made of plastic or gravel. Furthermore, wastewater in contact with the media, whether submerged or passed through, forms a slime-like layer that adheres to the media used to form a biofilm (68). The choice of wastewater treatment technology with a biofilter process is due to its advantages. Several advantages of using biofilters to treat wastewater include good efficiency in the biological decomposition of wastewater (69). However, the biofilter's

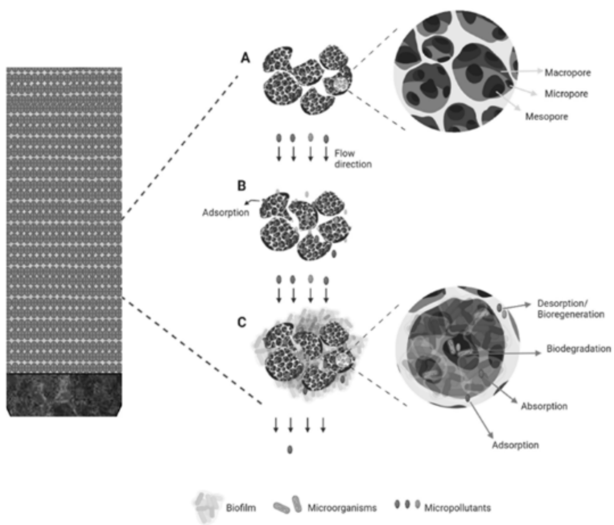

Figure 5. Reactor schematic diagram of (A) media structure, (B) adsorption of micropollutants on the media surface, and (C) pollutant removal mechanism in the media. Reproduced from Ajaz et al (62) under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

efficiency depends on the wastewater's contact area with the microorganisms attached to the selected filter media. Biofilters have good capabilities for reducing or even eliminating organic content in wastewater. Some contents that can be removed or reduced include COD, biochemical oxygen demand (BOD), ammonia, suspended solids, phosphorus, and even *Escherichia coli*, which can be reduced or removed with a biofilter system. In addition, this biofilter technology is a simple technology and relatively easy to operate. The application of this biofilter does not require chemicals or using large amounts of energy. In addition to their advantages, biofilters also have disadvantages in their systems. One of the disadvantages of this biofilter is that its performance efficiency is not always good. This is because the types and materials of the attached growth media were not the same. Cuttlefish bone medium is also known to be an easily accessible natural source that provides new, cheap, and safe antimicrobial agents. Studies have shown that cuttlefish bone extract has effective antimicrobial activity against various types of pathogenic bacteria and fungi (70). This shows the potential use of cuttlefish bone media as an alternative for the development of media for biofiltration, to eliminate harmful pathogenic bacteria. The use of cuttlefish bone media in biofiltration can be an environmentally friendly and effective solution to overcoming the problem of pathogenic bacteria. In addition, it was explained by Vilando et al (71) biofilters are only suitable for application in waste processing with a capacity that is not too large. This means that biofilters are less capable of processing wastewater with a large capacity and a very high organic content.

In a biofilter reactor, microorganisms cover the medium, allowing water-containing pollutants to flow through gaps and come into contact with the microbial mass layer (biofilm). Biofilms consisting of bacteria, fungi, algae, and protozoa degrade organic compounds in water. A thicker biofilm layer reduces oxygen diffusion, creating an anaerobic environment in the upper biofilm layer. The mechanism that occurs in a submerged quiescent attached reactor is as follows:

A. Transport and adsorption of organic substances and nutrients from the liquid phase to the biofilm phase.
B. Transport of microorganisms from the liquid phase to the biofilm phase.
C. Adsorption of microorganisms that occurs in the biofilm layer.
D. The metabolic reactions of microorganisms in the biofilm layer enable growth, maintenance, death, and cell lysis.
E. Attachment of cells occurs when the biofilm layer begins to form and accumulates continuously and gradually in the biofilm layer.
F. Release mechanism (biofilm detachment) and other products (by-products).

The growth of microorganisms in slime increases its thickness, causing food and O_2 diffusion to reach the solid surface. This resulted in the biomass layer being divided into aerobic and anaerobic layers. As the biofilm layer thickens, the adhesion of microorganisms weakens, leading to peeling off of the biomass layer. Aerobic efficiency decreases with increasing layers and the thickness of the anaerobic layer.

Several wastewater sources have been used in research related to biofilters, and their ability to reduce biological and COD by 43.75% using municipal wastewater (72). It is also interesting to note that biofiltration can be applied to oil refinery wastewater within 170 days using plastic media at a laboratory scale. It can reduce COD by up to 46% (73). In addition, it was found that the use of 80 cm-thick waste for 12 months in a pilot-scale study reduced biological oxygen requirements by 99% and chemical oxygen requirements by 98% (74).

Another interesting finding is that 69% of the data show that biofiltration research to reduce biological and COD was carried out for more than 10 days. With a maximum research time of 460 days, the media used was compost with a wastewater source in the form of a lab-scale Cheese Whey with a thickness of 0.15 m, and the results obtained reduced biological oxygen demand by 70%-80%, COD by 80%-88% (75). Further studies were conducted using school wastewater with a research period of more than 12 months on a pilot scale using sand, gravel, and coarse media of different thicknesses resulting in a reduction of 98% in biological oxygen requirements and 96% in chemical oxygen requirements. Uniquely, even though 69% of the research was carried out over a long period, research in a short period could also reduce COD by 80-90% using winery wastewater for 8 days on a lab scale with 75 liters of water.

Several types of media are used in the biofiltration process to reduce biological and chemical oxygen requirements, including sand (76), gravel, coarse (77), aged refuse (74), Corbicula fluminea (78), ashing rings (79), plastic (73), date kernel (72), pozzolan and sawdust (80), vermicompost (81), yeast (82), and compost (75). This shows that various types of media with various thicknesses can reduce biological and chemical oxygen requirements. Interestingly, sand, gravel, and Coarse sand were the best media for reducing the biological oxygen requirements (98%) and chemical oxygen requirements (96%) (77) compared with other media, without considering the type of wastewater being treated. This requires a more in-depth study of which media is best used as biofilter media by looking at the same kind of wastewater source.

The best reduction in biological and chemical oxygen needs occurs when using sand, gravel, and coarse media, namely 98% and 96%, respectively in school wastewater with a thickness of 0.6 m with a trial period of more than 12 months (77). This large reduction also occurred in old waste media with a reduction in biological and chemical oxygen requirements of 99% and 98%, respectively, using 80 cm thick leachate waste for 12 months (74). A different result was shown by a biofilter with plastic media that attempted to reduce COD in oil refinery wastewater for 170 days with only a 46% reduction in COD (73). This may occur because the type of waste is different and more concentrated compared to other wastes with different densities, so the biofilter is not able to optimally reduce pollutants in the waste.

Research conducted by Dorji et al (83) stated that up to 80% of the total suspended solid content was lost during a 262-day pilot trial using plastic bottles (PP and PET) at an average temperature of 23.4 °C. In addition, the same study showed that plastic media could eliminate up to 92.4% of *E. coli* (83). Total suspended solids can also be a good source of heavy metals (84). This is of course very dangerous for water if these substances are found in wastewater.

In addition to plastic media, several media can reduce *E. coli*, one of which was revealed in a previous study (85), showing that Corbicula fluminea used as a medium in biofiltration reactors can help consume *E. coli* from contaminated water. However, other studies have shown that the media can be saturated to reduce *E. coli* in wastewater as stated in the research by Mohanty et al (86), indicating that the removal of bacteria in the augmented biochar model biofilter was not affected by the influent concentration of *E. coli*. At a concentration of ~107 CFU mL^{-1}, the removal decreased to 91%, indicating that some portions of the medium may have reached a saturation point to degrade *E. coli*.

Wastewater treatment by a biofilter involves wastewater flow into a biological reactor (87). This biological reactor was previously filled with buffer media, which functions to reproduce microorganisms. This biofilter system can be operated using aerobic, anaerobic, or a combination of aerobic and anaerobic methods. Anaerobic processes do not involve the use of air or oxygen. However, if the process is performed aerobically, oxygen must be added. However, the use of an aerobic system is usually chosen to process loads that are not too large. Therefore, the aerobic system is typically used after passing through the anaerobic system in the previous process (88).

The principle of attached growth (biofilm), as explained in the study by Butler et al (89), is that biofilms are one of the main components or mechanisms by which microbial growth is attached. Biofilms have a complex structure. Biofilms are consortia (collections) of heterogeneous cells that are significantly influenced by the environmental conditions in which they live. Biofilms respond to the environment. Biofilm formation and growth have several requirements. The minimum requirements for biofilm formation are the surface, water, and nutrients. Biofilm formation also goes through a series of phases in general, namely, the media surface, colonization, and growth. Biofilm structures can be classified as smooth, dense, smooth, rough, flat, or stringy. The structure of this biofilm is influenced by several factors, including the chemical composition of the surrounding medium and the hydrodynamics of the existing system. The concentration of nutrients in the water can influence biofilm formation on the surface of the media.

Commonly used biofilter types in wastewater treatment

Biofilters with submerged beds

One of the characteristics of submerged-bed biofilters is that fixed (nonmoving) media are always submerged in water (90). The materials utilized in the biofilter medium of these filters, which serve as the attachment surface for bacteria, vary considerably. These materials include plastic screens, solid plastic beads, gravel, oyster shells, and extruded or molded high-surface area plastic rings. The diversity of materials allows for different surface areas for bacterial colonization, leading to efficient biological filtration (91). The submerged nature of media ensures constant contact between water and bacteria, thereby promoting optimal nutrient removal in aquatic environments (92,93).

Three categories of submerged bed biofilters exist based on the direction of water movement: downflow biofilters work by allowing water from the clarifier to enter the top of the filter by gravity, pass through the filter to a sump, and then, pump the oxygenated water to a head tank, where it flows to the fish culture tanks by gravity. Downflow filters require frequent backwashing due to their susceptibility to clogging. However, they are the easiest and the least expensive to build. Backwashing with high air volumes has also been successful in removing particulate matter. However, upflow biofilters operate by pumping water from the clarifier to the bottom of the filter, allowing it to rise through the medium and exit at the top. Upflow filters are less prone to clogging than downflow filters. However, they require more energy for their operation (94). Additionally, crossflow biofilters combine the elements of both downflow and upflow systems, thereby providing a balance between the efficiency and maintenance requirements (95).

Upflow filters have an advantage over downflow filters because a settling basin can be added beneath the medium. Upflow filters function under gravity, similar to downflow filters. Generally, a buoyant lightweight medium is required. Determining when to clean the settling basin when it is positioned beneath the biofilter is challenging (94). The majority of dissolved oxygen in settling basins can also be used by heterotrophic bacteria, which lowers the effectiveness of the biofilter (96). The deepest that the upflow and downflow filters can go without additional in-filter oxygenation is approximately 40 inches.

Water enters lateral-flow biofilters and moves laterally through the media. A tiny chamber and a portion of the medium are used in the commercially available design of this type of device to remove particle trash. An airlift was built into the biofilter to return water from the filter to the fish-rearing tank. The suitability of this system for large-scale manufacturing has not been determined. However, lateral-flow biofilters are generally more efficient in removing solid waste than upflow and downflow filters. The use of airlifts in biofilters can also help improve oxygenation levels in water, thereby promoting a healthier environment for aquatic organisms. Lateral-flow biofilters are often preferred over other types of biofilters in terms of cost-effectiveness and ease of maintenance. The incorporation of airlifts into biofilters can contribute to a more sustainable and environmentally friendly aquaculture system (97).

Trickling filters

Water enters the trickling filters at the top and passes through the medium below, similar to submerged downflow filters. However, the trickling filter has an open bottom and is raised (Figure 3). Because of this arrangement, the medium can be exposed to air, thus, guaranteeing bacterial oxygen. A trickling filter and packed column aeration/gasification system were operated according to the same principles (98). The primary distinction is that trickling filters are primarily used for wastewater treatment, whereas packed column systems are typically employed for aeration and degasification (99). To encourage bacterial activity and oxygen transfer in both systems, the medium must be exposed to air. In general, the promotion of bacterial activity and oxygen transfer in water treatment processes can be achieved using both trickling filters and packed column aeration/degasification systems. The secret lies in the configuration and design of the system to guarantee the maximum effectiveness and performance (100).

The sloughing of bacteria is an issue in trickling filters. Occasionally, this happens to a large enough extent to drastically reduce the nitrifying ability of the filter. The trickling filter system must be regularly inspected and maintained (101). Redundancy or backup mechanisms built into the architecture help reduce treatment process interruptions caused by bacterial loss. Regular monitoring and maintenance of the trickling filter system are essential to prevent excessive sloughing and maintain efficient treatment. Incorporating backup systems or redundancy in the design can help minimize disruptions in the treatment processes due to bacterial loss. Over time, these steps guarantee the peak performance and efficiency of the system.

Rotating disk

Recently, there has been an increase in the use of rotating disc biofilters, also known as rotating biological contactors or rotating biocontactors, in this system (Figure 4). A set of parallel circular plates with a tiny (0.25–0.5 inches) space between them set on a shaft serves as the nitrifying bacterial substrate. A paddlewheel powered by water flow or a low-speed gear motor rotates the discs on the shaft while they are partially submerged. These units are typically arranged sequentially. Rotating disc biofilters provide a large surface area for the growth of beneficial bacteria, which helps break down organic matter and remove pollutants from the water. This system is known for its efficiency in treating wastewater and maintaining water quality in various applications such as aquaculture and municipal sewage treatment plants. The design of rotating disc biofilters allows efficient oxygen transfer to nitrifying bacteria, thereby promoting their growth and activity (102). This results in the effective removal of ammonia and other nitrogen compounds from the water, making it suitable for discharge or reuse.

The benefits of rotating biological contactors (RBCs) include their propensity for self-cleaning, low head needs, and the capacity to sustain high dissolved oxygen levels. The nitrification process is constant because of the rotation, which keeps a thin layer of water exposed to the air and provides bacteria with sufficient oxygen. Fluctuations in the water flow, dissolved oxygen changes, and partial blockage can cause variations in the nitrifying capability of other systems. However, the rotating disc biofilter design helps mitigate these issues by ensuring consistent exposure to oxygen and preventing blockage (103). Overall, this system offers a reliable and efficient solution for wastewater treatment, with minimal maintenance requirements. In addition, the rotating disc biofilter also promotes the growth of beneficial bacteria that aid in breaking down organic matter and reducing harmful pollutants in water. This results in improved water quality and a more sustainable treatment process overall (44).

Rotating disc biofilters have several drawbacks, including a small surface area, high operating costs, and a propensity for evaporative water cooling. Because the size of the biofilter depends on the surface area of the nitrifying bacteria, a sizable space is required to install this filter system. Most rotating disc biofilters require an additional motor for their operation. Thus, it is necessary to consider the cost of operating the motor and the additional maintenance required (104). Additionally, evaporative water cooling can lead to fluctuations in the water temperature, which may not be ideal for certain aquatic species. It is important to consider these factors when determining the best filtration system for a specific aquatic environment. Furthermore, the noise generated by the motor may also be a concern, especially in indoor settings or in areas where noise pollution is considered. Before making a decision, it is important to weigh the benefits of a rotating disc biofilter against these potential drawbacks.

Evaporation, which is the second issue with spinning disc biofilters, only affects systems with high air exchange rates. The technique by which a small layer of water is continuously exposed to air via a rotating disc is the same as that used by many household humidifiers. This change in temperature in the culture tanks must be considered because evaporation produces cooling. Systems with revolving disc biofilters are generally advised to be housed in insulated firmly closed buildings. Furthermore, a secondary clarifier is necessary because of the self-cleaning nature of spinning disc biofilters. This clarifier helps to remove any solids that may accumulate during the biofilter process, ensuring that the water remains clean and clear. In addition, regular monitoring and maintenance of the biofilter system are essential to ensure optimal performance and efficiency. This includes checking for any clogs or blockages in the system, as well as monitoring water quality parameters, such as ammonia and nitrate levels. By staying on top of the maintenance tasks, aquaculture operators can prevent potential issues and ensure the longevity of their biofilter system.

Dynamics of bacterial communities in biofilter

Naturally occurring microbial communities can evolve in engineered systems even if the operational and physicochemical parameters remain unchanged (105). However, the response usually takes longer than one day compared to young biofilms (during acclimation), where significant changes usually require more than one day (106,107). The process of microbial evolution in engineered systems can be slower than that in young biofilms, but significant changes can still occur, even though it takes longer. The diversity of microbes in biofilms can influence the time required to respond to environmental changes (108).

Biofilter bacterial communities were differentiated according to the depth of the filter layer. Fast-growing and less-specialized bacterial communities are usually adapted in the upper part of the filter layer for the efficient utilization of the easily biodegradable dissolved organic carbon (DOC) fraction in the deeper parts. In In the bottom layer of the filter, more specialized bacterial communities are expected to develop, feeding on less biodegradable and complex organic substances, which typically require a more diverse microbial community (109). This more specialized bacterial community at the bottom of the filter assists in the breakdown of more complex organic substances, enriching the microbial diversity for efficient biodegradation processes. This demonstrates the important role of various types of bacteria in maintaining the balance of the biofilter ecosystem. The diversity of microbes in the filter can also increase the efficiency of the biodegradation process, thereby ensuring that the water quality is maintained (110,111).

It is also worth considering the use of *Sporosarcina halophila* in the biofiltration process. *S. halophila* is a powerful strain for producing biosurfactants because its metabolites have emulsifying properties. It was also found that this biosurfactant can be used in various industrial or environmental applications, including soil or water bioremediation by the *S. halophila* strain to remove crude oil (112). This can be a great potential in the pollutant reduction process in biofilters.

Changes in pH cause changes in the selection pressure on microbes, thereby supporting the growth of bacteria that can tolerate a certain pH. Therefore, monitoring and regulating the pH in biofilters is essential to ensure optimal environmental conditions for microbes. Thus, the role of bacteria in maintaining the balance of the biofilter ecosystem can continue to be efficient. Numerous types of bacteria are present in biofilter reactors, the majority of which are well known for their existence and advantages.

Contaminant removal mechanisms

The exact process by which a biofilter removes pollutants from water depends on the type and age of the filter medium. For example, in a biofilter with sand media, pollutants are removed through physical filtration and biological degradation by microorganisms living on the surface of sand particles (113). As the filter media ages, the microbial community becomes more established and efficient at breaking down pollutants (114,115).

For non-porous biofilter media, such as sand, the main removal mechanisms are filtration and biodegradation. For porous biofilter media, various mechanisms are involved in different stages of the biofiltration process. The dominant removal mechanism of pollutants in biological reactors is absorption by biofilms followed by biodegradation by microorganisms (116). Combining these mechanisms allows for effectively removing a wide range of contaminants from wastewater, making biofiltration a sustainable and environmentally friendly treatment option.

Biofilms provide habitats for microorganisms that feed on pollutants (117,118). Organic compounds are biodegraded either by direct catabolism or co-metabolism (119). Biofilms can also protect microorganisms from harsh environmental conditions such as high levels of toxins and UV radiation. Additionally, biofilms play a crucial role in nutrient cycling and can affect overall ecosystem health (64).

Primary and secondary substrates are catabolized by specific enzymes and are used as carbon and energy sources by microorganisms (120,121). The primary substrate in most drinking water and wastewater biofilters is dissolved organic matter, which consists of both natural and anthropogenic compounds (122,123). The breakdown of these substrates releases nutrients that can be utilized by other organisms in the ecosystem, contributing to the overall productivity and functioning of the environment

(124,125). Biofilms are essential components of aquatic ecosystems that influence water quality and support diverse microbial communities (126).

Pollutants, which generally occur at low concentrations, are removed by utilization of secondary substrates or co-metabolism (127,128). This process helps break down pollutants and reduce their harmful effects on the environment (129). Biofilms play a crucial role in maintaining aquatic ecosystems (130,131). Biofilms are essential for the overall health of aquatic environments as they contribute to the natural degradation of pollutants. This intricate process not only helps reduce the harmful effects of pollutants but also supports the sustainability of diverse microbial communities in water bodies (132).

Pollutant biodegradation depends on various factors such as nutrient availability, oxygen concentration, pH, concentration, bioavailability of contaminants, and physical and chemical characteristics of the biomass (133). Bioregeneration is another mechanism that aids the removal of pollutants from filters. This is the ability of a biofilm to renew adsorption sites in the medium because of its microbial activity (134). Bioregeneration leads to renewed adsorption capacity, higher system stability, and a longer lifetime of activated carbon (135).

The exoenzyme reaction is one of the processes that drives bioregeneration. Exoenzymes released by biofilm-forming bacteria are assumed to permeate into the activated carbon pores, where they interact with the adsorbed substrate. Because of their reduced absorption capacity, metabolites can be absorbed and the substrate or the resultant enzyme can undergo hydrolytic breakdown (136). This process helps regenerate activated carbon, allowing it to maintain its adsorption capacity over a longer period. By using bioregeneration, the system stability and lifetime of activated carbon can be significantly increased.

Biodegradation of organic materials adsorbed onto active carbon sites during bioregeneration can also release any pollutants that bind to them. These pollutants are metabolized or absorbed depending on their characteristics (137). Bioregeneration depends on factors such as the absorbency of the substrate (contaminants), the presence of microorganisms capable of metabolizing the adsorbate, prevailing environmental conditions such as nutrients and dissolved oxygen, and temperature required for optimal microbial growth (138,139). The success of bioregeneration also relies on the ability of microorganisms to effectively break down pollutants, thereby highlighting the importance of a conducive environment for microbial growth (140).

Conclusion

These findings suggest that biofilms degrade organic compounds, reduce oxygen transport, and create anaerobic environments. Through the thickening and separation of biomass into aerobic and anaerobic layers, aerobic efficiency is reduced and adhesion is impeded. The development of microorganisms depends on these factors. Additionally, biofilms help shield bacteria from external stimuli and antimicrobial substances, increasing their resistance. To manage and control microbial populations, it is essential to understand how biofilms affect their growth. Submerged-bed biofilters, trickling filters, and packed column aeration and gasification systems can be used to remove nutrients from aquatic environments. By offering a surface for biofilm growth, these systems enable microorganisms to decompose organic materials and extract nutrients from the water.

Rotating disc biofilters are being increasingly used in wastewater treatment to efficiently remove pollutants and promote bacterial growth. Although significant alterations in microbial communities within artificial systems occur more slowly than in juvenile biofilms, the variety of microorganisms within the system may influence the reaction time. These systems can arise from microbial populations. The biofilter bacterial communities were categorized according to the depth of the filter layer. More specialized communities were located in the bottom layer, while less specialized, faster-growing communities were found in the upper layer. Changes in pH in biofilters promote the growth of bacteria, making it necessary to monitor pH levels, regulate ideal environmental conditions, and rely on bacteria to effectively maintain the balance of the biofilter ecosystem. Monitoring and regulating the pH levels in biofilters is crucial for maintaining the balance of the ecosystem, as it directly affects the growth of bacteria. By ensuring ideal environmental conditions, microbial communities can thrive and effectively remove contaminants from a system. Depending on the type and age of the medium, biofilters can efficiently remove pollutants. Non-porous media use filtration and biodegradation, whereas porous media use biofilm absorption and microbial biodegradation. Biofilms provide habitats for microorganisms, break down organic materials, shield ecosystems from adverse weather, and are essential for the cycling of nutrients, all of which have an impact on ecosystem health. Enzymes affect water quality, support a variety of microbial communities, catabolize organic matter in wastewater and water biofilters, and supply microorganisms with carbon and energy. Enzymes play a crucial role in maintaining ecosystem balance by breaking down pollutants and supporting microbial life. Their presence in biofilters helps improve water quality and ensure the health of aquatic environments.

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Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

Ethical issues
There is no ethical issue. The authors declare that all data collected during the study are as stated in the manuscript and that no data from the study have been or will be published separately elsewhere.

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