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A Mini Review on Biofilm-Mediated Water Pollution: Mechanistic Interactions, Preventive Approaches, and Removal Strategies

Anati Abd Rashid Syaida[1], Mohd Taufiq Mat Jalil[1], Mohd Muzamir Mahat[1], Rikson Siburian[2] and Mohd Fakharul Zaman Raja Yahya[1,3*]

[1]*Faculty of Applied Sciences, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Selangor, Malaysia*
[2]*Faculty of Mathematics and Natural Sciences, Universitas Sumatera Utara, Medan 20155, Indonesia*
[3]*Integrative Pharmacogenomics Institute (iPROMISE), 42300 Bandar Puncak Alam, Selangor, Malaysia*

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ABSTRACT

Biofilm formation significantly contributes to water pollution and infrastructure degradation in various industrial, urban, and marine environments. Biofilms can colonize various surfaces, including sediments, plants, and man-made structures. This colonization negatively impacts water quality and the integrity of water distribution systems. Biofilms can also harbor pathogenic microorganisms, posing health risks in drinking water systems. This mini-review discussed how biofilm-related processes, such as clogged pipes, bio corrosion, and marine biofouling, can lead to water pollution and their broader environmental and economic implications. Biofilm buildup can trap contaminants, weaken pipe structures, cause localized corrosion, increase the surface roughness of ship hulls, and contribute to higher operational costs and harmful emissions. Surface modification and managing hydrodynamic conditions effectively mitigate water pollution in various aquatic environments. Effective biofilm removal strategies include high-pressure water jets, ultrasonic treatment, enzyme-based cleaning, and oxidizing agents. In conclusion, biofilms are a major contributor to water pollution and infrastructure damage across various environments, highlighting the urgent need for innovative and effective biofilm management strategies. Combined with regulatory frameworks and public awareness, these measures can significantly reduce biofilm-mediated water pollution's environmental and economic impacts.

* Corresponding author. *E-mail address*: fakharulzaman@uitm.edu.my

INTRODUCTION

Biofilms are complex communities of microorganisms that attach to surfaces and are embedded within a self-produced matrix of extracellular polymeric substances. These biofilms can form on various surfaces in aquatic environments, including natural water bodies and man-made water distribution systems.

Biofilm formation in water systems poses significant challenges due to its impact on water quality and public health. The colonization of biofilms on various surfaces can lead to the deterioration of water infrastructure and the contamination of water supplies with pathogenic microorganisms (Moyal et al., 2023). Biofilms contribute to several physicochemical changes that degrade water quality. These changes include the alteration of watercolor, taste, and odor, which can result from the metabolic activities of the biofilm's microbial community (Erdei-Tombor et al., 2024). Moreover, biofilms serve as reservoirs for pathogens, such as Legionella and Pseudomonas, which pose significant health risks to humans (Wingender et al., 2011). The presence of biofilms can facilitate the survival and proliferation of these pathogens, making them difficult to eradicate from water distribution systems. Furthermore, biofilms can interact with and sequester pollutants, including heavy metals and organic contaminants, thus impacting the bioavailability and toxicity of these substances in the environment (Dar et al., 2020). While biofilms can aid in the degradation of pollutants through bioremediation processes, their presence can also exacerbate pollution problems by acting as sources of secondary contamination, such as microplastics (Kalčíková et al., 2022).

Biofilms in water distribution systems, cooling towers, and pipelines can contribute to spreading infections (LeChevallier et al., 2024), particularly in public health settings such as hospitals, where immunocompromised individuals are more susceptible to these diseases. Pathogens can thrive within biofilms, facilitating their transmission through drinking water, recreational water, and other water sources (Kaplan 2010). In biofilms, these pathogens are shielded from environmental stressors and antimicrobial agents, making them more resistant to conventional water treatment methods such as chlorination and filtration. Consequently, individuals exposed to contaminated water are at higher risk of contracting waterborne diseases, including gastrointestinal infections, cholera, Legionnaires' disease, and other illnesses caused by enteric bacteria. On the other hand, biofilms' metabolic activities can cause biofouling, which reduces the efficiency of water treatment processes and the overall performance of water distribution networks (Li et al., 2023). This biofouling can lead to clogging, corrosion, and the need for more frequent cleaning and disinfection procedures, further contributing to operational challenges and financial burdens.

This mini-review explores the multifaceted roles of biofilms in aquatic environments, emphasizing their formation, structure, and impact on water quality, public health, and infrastructure. It addresses the mechanisms through which biofilms contribute to pollution, including contamination with pathogens and interactions with pollutants such as organic wastes. The review highlights the health risks associated with biofilm-associated pathogens, particularly in water distribution systems, where they exhibit resilience against conventional treatments. Additionally, the operational challenges posed by biofilm-induced biofouling, clogging, and biocorrosion are discussed, alongside strategies for their prevention and removal, such as advanced cleaning technologies and surface modification techniques.

Fundamental Concept of Biofilm

Biofilms are structured communities of microorganisms that adhere to surfaces and are encased in a self-produced matrix of extracellular polymeric substances (EPS) (Yahya et al. 2017; Yaacob et al. 2021; Johari et al. 2023). The formation of biofilms begins with the initial attachment of free-floating microbial cells to a surface (Figure 1). Environmental factors such as nutrients, surface characteristics, and hydrodynamic conditions often facilitate this attachment. Once attached, the cells produce EPS, which helps establish and stabilize the biofilm community. The growth of biofilms is characterized by the proliferation of microbial cells within the EPS matrix, leading to the development of complex, three-dimensional structures. These structures can include channels and pores that facilitate the distribution of nutrients and the removal of waste products. Various environmental factors influence biofilm growth, including light, temperature, and nutrient availability (Rummel et al. 2017). According to Sharma et al. (2023), the biofilm lifecycle involves stages of maturation, where the biofilm reaches a stable state, and dispersion, where cells or clusters of cells are released to colonize new surfaces. In biofilm research, 6-well and 96-well microplates are often used for quantitative biomass measurement and structural characterization (Amran et al. 2024).

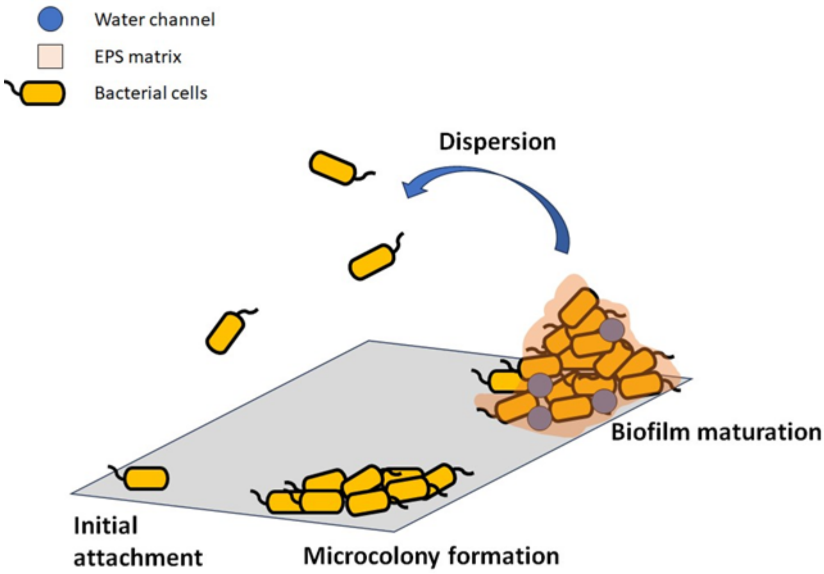

Fig. 1. Life cycle of microbial biofilm.

Biofilms play a significant role in environmental pollution, both as contributors to and mitigators of pollution. Biofilms can colonize various surfaces in aquatic environments, including sediments, plants, and man-made structures. This colonization can lead to biofouling, negatively impacting water quality and water distribution systems' integrity. Conversely, biofilms also have beneficial roles in environmental pollution control. They are used in bioreactors for wastewater treatment, where microbial communities within biofilms degrade organic pollutants and remove harmful substances from water. Biofilms can also facilitate the biosorption of heavy metals and other contaminants, making them useful in bioremediation efforts (Sharma, 2022). Moreover, natural biofilms in the environment can contribute to the breakdown and removal of pollutants, which is crucial in maintaining ecological balance (Yadav, 2017). The dual role of biofilms in environmental pollution highlights their complex nature. While they can contribute to pollution and infrastructure problems, they also offer potential solutions for pollution control and environmental cleanup. Understanding the dynamics of biofilm formation and growth is essential for developing effective strategies to manage their impact on the environment.

Mechanisms of Biofilm-Mediated Water Pollution

One notable interaction is the adsorption of pollutants onto the biofilm surface. Biofilms can act as a sink for pollutants, effectively concentrating them within the biofilm matrix. This process can include the adsorption of heavy metals, polycyclic aromatic hydrocarbons (PAHs), and other hazardous substances. The EPS matrix, rich in polysaccharides, proteins, and nucleic acids, provides numerous binding sites for these contaminants, facilitating their sequestration. Priyadarshanee and Das (2023) have shed light on the fact that the specific glycosyltransferases, polymerase, and transporter proteins are responsible for the structural and functional diversity of the extracellular polymer. Agrobacterium, Pseudomonas, Enterobacteriaceae, and Xanthomonas have all been shown to include operons that contain certain genes like *crd, alg, wca*, and *gum.* These genes are responsible for encoding the enzymes. The operons are responsible for regulating the manufacture of extracellular polymers, such as curdlan, alginate, colonic acid, and xanthan, in chronological order. The EPS contains several functional groups, including carbonyl, hydroxyl, phosphoryl, and amide (Yahya et al., 2018; Yaacob et al., 2021; Kamaruzzaman et al., 2022), which serve as the sorption site for the interaction with environmental contaminants (Qu et al., 2022). Hydrophobic interactions and coordination bonds are the primary factors when binding EPS with environmental contaminants as they dominate.

The carbonyl group, characterized by a carbon atom double-bonded to an oxygen atom (C=O), is a prominent functional group in organic chemistry. It is highly reactive due to the carbon-oxygen double bond's polarity, making it an effective sorption site for various contaminants. Carbonyl groups can form hydrogen bonds and coordinate with metal ions, thereby facilitating the adsorption of organic and inorganic pollutants. Studies have shown that carbonyl-containing compounds play a significant role in binding heavy metals, thus influencing their mobility and bioavailability (Javanbakht et al., 2014). The hydroxyl group (–OH) is another functional group crucial for sorption. This group is highly polar, allowing it to form strong hydrogen bonds with water molecules and various contaminants Priyadarshanee and Das (2023). Hydroxyl groups are abundant in natural organic matter, such as humic substances, which play a vital role in the environmental chemistry of water bodies. The presence of hydroxyl groups enhances the solubility of organic compounds and their interaction with pollutants, including pesticides and pharmaceuticals. These interactions can lead to the adsorption of contaminants onto soil and sediment particles, affecting their persistence and transport in the environment. Phosphoryl groups ($–PO_4^{3-}$) are critical in environmental chemistry due to their strong affinity for metal ions and organic pollutants. Phosphoryl groups in compounds like phospholipids and nucleotides enable them to effectively bind with heavy metals such as lead, cadmium, and mercury. This binding reduces the bioavailability of these metals, thereby mitigating their toxic effects on aquatic and terrestrial ecosystems. Phosphoryl groups also play a role in the sorption of organic contaminants, such as herbicides and insecticides, influencing their distribution and environmental degradation.

Kurniawan and Fukuda (2022) investigated the electrophoretic mobilities of biofilms grown on stones after 15, 30, and 60 days of formation. They also studied copper (II) adsorptions by mature biofilms at varying pH levels (pH 9, 7, 5). The study's findings revealed that the amount of copper (II) adsorbed onto the biofilms varied depending on the pH value. Specifically, the amounts were 92, 73, and 21 µmol/g at pH 9, 7, and 5, respectively. It is possible that the presence of a large number of negatively charged sites in the biofilm polymers used in natural aquatic environments was the cause of the highest concentration of copper ion (Cu(II)) at pH 9. Other works on biofilms and their interaction with materials commonly found in water facilities are summarized in Table 1.

Table 1. Material interactions with biofilm formation and their implications for water pollution and infrastructure integrity.

Authors	Findings
Avgoulas et al., (2024)	Passivated stainless steel and Ti-6Al-4V (Ti) alloy promote the proliferation of certain microbiological colonies. Applying shear stress reduces bacterial adhesion to the examined materials, with the extent of reduction dependent on the type of materials.
Im et al. (2024)	Cast iron (7.10 ± 0.78 nm) has a rougher surface than PVC (5.60 ± 0.14 nm) and is positively charged, making it ideal for biofilm growth. Over 425 hours, the fouling layer on cast iron and PVC surfaces increased in thickness, porosity, roughness, and density.
Pan et al. (2024)	For patients who have had pancreatic surgery, a unique pancreaticojejunostomy device that is 3D-printed and has a nano-silver antibacterial coating may avoid infection and pipe clogging. This device can prevent duct obstruction caused by bacterial biofilms.
Wang et al. (2023)	Biofilms change the surface charge, physical roughness, and electrostatic interaction between porous medium and suspended particles. Biofilms bind and adhere to suspended particles to create compact biofilm-particle aggregations. As biofilm thickness grew, more suspended particles were deposited on the sand surface.
Ying et al. (2023)	Elevated chlorine concentrations may induce bacteria to produce greater amounts of extracellular polymeric substances (EPS), establishing a coexistence system with entrapped particles and natural organic matter (NOM) inside the porous medium. Thus, this facilitated the development of biofilms, thus increasing the risk of aquifer clogging.
Ibrahim et al., (2023)	The microbial counts are often greater near the entry of the internal water line surface than at the terminus. Forty-five percent of the isolates responsible for moderate biofilm formation are *P. aeruginosa* and *K. pneumoniae*, potentially jeopardizing animal health in future production cycles.
Kaur et al. (2020)	The presence of certain pathogenic microbes, such as Shigella, *E. coli*, *Vibrio cholerae*, Pseudomonas, and Salmonella, in drinking water can negatively impact water quality. Pathogens entering the water distribution system can form biofilms, an important aspect of microbial studies in this context.
Liu et al. (2016)	Biofilms are the predominant mode of microbial growth in drinking water distribution systems, and their formation poses significant problems, including bacterial contamination, taste and odor issues, and pipe corrosion.
Hemdan et al., (2016)	Plastic-based pipe materials like PVC, PP, and PE have a steady-state biofilm formation in 70 days for both *L. monocytogenes* and *S. Typhimuruim*. Corroded pipe materials (R) show a shorter steady-state time for *L. monocytogenes* (60 days) and a longer one for *S. Typhimuruim* (80 days).
Wang et al., (2012)	Dense oxide layers and biofilm formation inhibit iron corrosion and reduce chlorine decay in the system. Iron-oxidizing bacteria (IOB) and iron-reducing bacteria (IRB) synergistically interact with the corrosion products to prevent further corrosion.

Clogged Pipes

One major problem caused by biofilms in water systems is the pipe diameter reduction due to microbial biomass accumulation. This can lead to significant clogs and blockages, impeding water flow and increasing the risk of pipe bursts. The biofilm's EPS matrix, being highly adhesive and resilient, makes mechanical removal challenging and often requires repeated or intensive cleaning efforts. As the biofilm matures, its structure becomes more complex, making it even more resistant to shear forces from water flow and other mechanical disturbances.

The presence of biofilms in pipes causes physical blockages and contributes to pipe damage, poor instrument performance, and the deterioration of water quality. Biofilms can harbor pathogenic microorganisms, which can be released into the water supply, posing health risks to consumers. Furthermore, the metabolic activities of biofilm-forming bacteria can produce harmful by-products, such as hydrogen sulfide, which can cause corrosion of the pipe material and further exacerbate clogging and blockage issues (Mahapatra et al. 2015). Research has shown that the biofilm formation process in water pipes involves initial microbial adhesion to the pipe surface, followed by the growth and development of a mature biofilm. Water temperature, flow rate, and nutrient availability significantly influence biofilm development. For instance, stagnant or low-flow conditions often promote biofilm growth by allowing microorganisms ample time to adhere to surfaces and multiply without being washed away. Additionally, organic and inorganic nutrients in the water provide the necessary resources for microbial proliferation and biofilm maturation.

Figure 2 shows a clogged pipe caused by biofilm formation. In this scenario, biofilms have developed on the interior surfaces of the pipe. These biofilms are composed of microbial cells encased in a self-produced extracellular matrix. This matrix contains negatively charged functional groups that allow it to trap various contaminants, such as organic waste, which further contributes to clogging and blocking water flow. The trapped contaminants may contribute to further pollution as they leach into the water system, potentially releasing harmful substances. In addition, increased pressure and biofilm buildup can weaken pipe structure, leading to potential damage. This biofilm-driven clogging in pipes is a common issue in industrial and environmental contexts, where water contamination and equipment performance degradation are concerns.

Wang et al. (2022) compared the dynamic bio-clogging processes that occur in pipes made of various materials, including high-density polyethylene (HDPE), polyvinyl chloride (PVC), polypropylene (PP), and polyethylene (PE). They also explored the association between these processes and the physicochemical features of materials. The bio-clogging that occurred in HDPE and PVC pipes was shown to be more severe than the bio-clogging that occurred in PP and PE pipes. During bio-clogging development, the electron donator parameter replaced the surface roughness as the most important factor. Both bacteria adhesion and EPSs secretion are key processes in bio-clogging development Carrel et al. (2018).

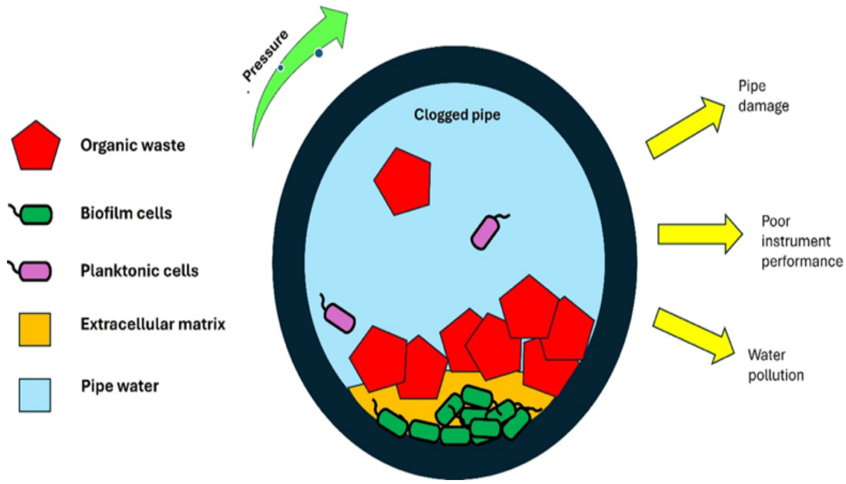

Fig. 2. Development of biofilms causing clogged pipe.

Biocorrosion

Microbial biofilms in water distribution systems can significantly impact pipe corrosion and water quality. These biofilms form when bacteria adhere to pipe surfaces, producing extracellular polymeric substances (EPS) that facilitate attachment and protection. The interaction between EPS and pipe materials influences bacterial community composition and micropollutant dynamics. Biofilms can enhance copper release in copper pipes by creating reactive interfaces and altering local microenvironments (Vargas et al., 2014). Biocorrosion, or microbiologically influenced corrosion (MIC), occurs when microbes directly cause corrosion through metabolite secretion, electron harvesting, or indirectly by compromising passive films on metal surfaces (Dou et al., 2020). Pathogenic bacteria in these biofilms pose health risks, as they can lead to various infections when consumed. Understanding these complex interactions is crucial for maintaining water quality and infrastructure integrity in distribution systems.

Figure 3 shows the stages of biofilm formation and biocorrosion on stainless steel, showing how microbial activity and the biofilm matrix contribute to pitting and the subsequent degradation of the material. This process occurs when microbial colonies, particularly bacteria, colonize a material's surface and begin secreting biofilm, a protective extracellular matrix. The biofilm provides an ideal environment for bacterial metabolic activity, contributing to localized corrosion. After initial attachment, bacteria produce a biofilm that traps nutrients, further encouraging microbial growth. The biofilm acts as a barrier, creating microenvironments on the stainless-steel surface. The biofilm environment can alter the electrochemical conditions on the surface, leading to pitting, a localized form of corrosion. This is depicted in the middle stages of the image. Metabolic by-products of the bacteria, such as hydrogen sulfide, can react with the metal, accelerating corrosion. This often results in the formation of pits, which can significantly weaken the material. Biofilm-induced corrosion requires extensive cleaning, repairs, or replacement, especially in industrial or water treatment systems. In addition, biocorrosion-induced leaks can result in costly repairs and pose environmental risks by allowing harmful substances to enter natural water bodies or groundwater systems, exacerbating pollution problems.

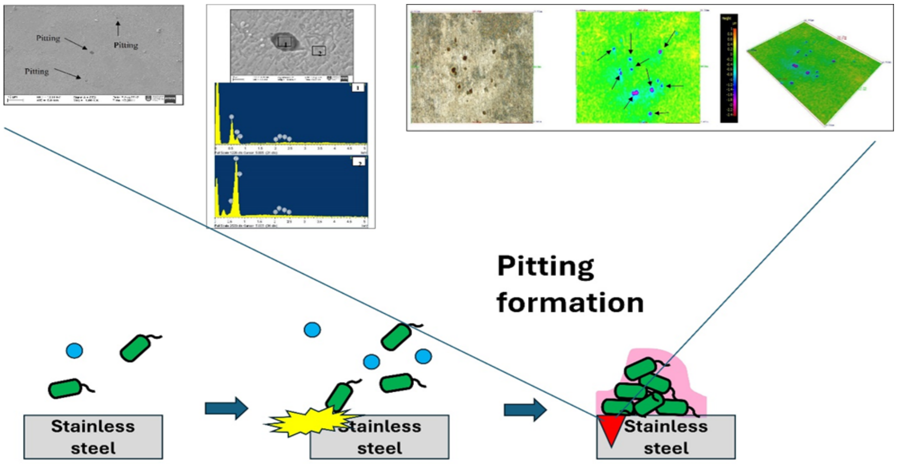

Fig. 3. Biocorrosion of a stainless steel-based pipe caused by biofilm formation on the steel surface. This illustration includes microscopic images of the surface damage, including scanning electron microscopy and other experimental results (e.g., energy-dispersive X-ray spectroscopy, infinite focus microscopy) that indicate the presence of pits on the stainless-steel surface. The pits are often deep, concentrated areas of corrosion that can lead to structural failure.

Yin et al. (2023) investigated the interaction between EPS and corrosion products on biofilm formation. They revealed that EPS's abundance of quorum sensing (QS)-related genes, polysaccharide, and amino acids biosynthesis genes was higher in cast iron pipes biofilms than stainless steel pipes. Polysaccharides in the EPS were more easily adsorbed onto the corrosion products in cast iron pipes, forming more biofilms containing human pathogenic bacteria carrying antibiotic resistance genes (ARGs). Furthermore, the amide I, amide II, and phosphate components of the EPS were more susceptible to the corrosion products in stainless steel pipes, leading to the formation of more biofilms containing bacteria carrying mobile genetic elements (MGE) and ARGs, which was attributed to the higher abundance of genes related to quorum sensing, amino acid biosynthesis, and lipid metabolism.

Marine biofouling

Biofilm formation on ship hulls, known as biofouling, significantly contributes to water pollution and increases fuel consumption. When microorganisms such as bacteria, algae, and diatoms attach to submerged surfaces like ship hulls, they form a biofilm (Snowdon et al., 2023). This biofilm traps organic matter and facilitates the growth of more complex organisms, including barnacles and mussels, leading to increased drag and resistance as ships move through the water. The rough surface caused by biofilm accumulation forces vessels to consume more fuel to maintain speed, increasing emissions of harmful pollutants like CO2 and nitrogen oxides (NOx) and contributing to atmospheric and marine pollution (Georgiades et al., 2023). Furthermore, biofouling can also result in the transfer of invasive species from one ecosystem to another, further destabilizing marine environments (Weber & Esmaeili, 2023). These factors make biofilm-mediated contamination a critical issue for the maritime industry, requiring regular cleaning and antifouling coatings to minimize environmental and economic impacts. Widely employed strategies for mitigating fouling can also result in considerable environmental impacts, including (1) chemical contamination stemming from the discharge of antifoulants from ship hull coatings, potentially intensified by in-water cleaning, and (2) the threat of disseminating non-indigenous species from fouled hulls due to compromised or ineffective hull coatings, or from uncontained waste during in-water cleaning of these hulls (Morrisey et al., 2013; Early et al., 2014).

Figure 4 depicts biofilm formation on a ship hull, highlighting how contaminants get trapped in the extracellular matrix of the biofilm, which contains various negatively charged functional groups. This biofilm, along with marine organisms like algae, sponges, and mussels, adheres to the ship's surface, causing several problems. The accumulation of biofilms increases the surface roughness of the hull, leading to a reduction in the ship's speed. More fuel is consumed to maintain speed, contributing to higher operational costs and harmful emissions like CO2. Also, biofilm and marine growth contribute to surface deterioration, increasing maintenance costs and frequent hull cleaning. These factors collectively elevate the environmental impact and operational expenses of maritime activities.

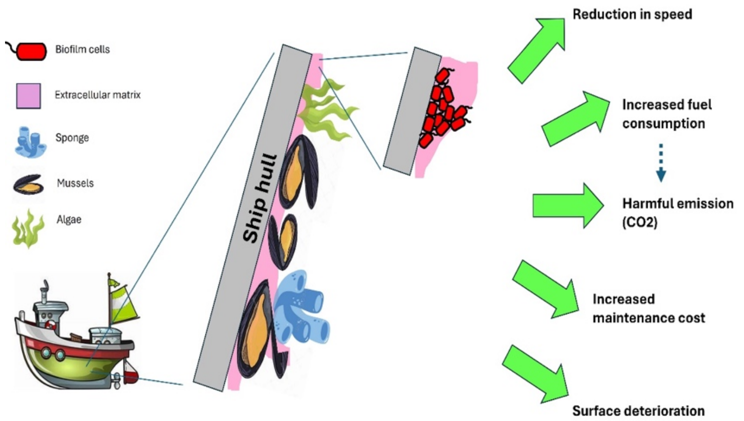

Fig. 4: Effects of biofouling on marine environment.

Oliveira and Granhag (2023) evaluated the effects of ship hull in-water cleaning on fouling-control coatings. Their findings indicated that bi-monthly or monthly cleaning, with a maximum wall shear stress of 1.3 kPa and a jet stagnation pressure of 0.17 MPa, did not seem to inflict damage or wear on either the biocidal antifouling (AF) or the biocide-free foul-release (FR) coatings. The AF coating required bi-monthly cleanings to maintain fouling at the incipient slime level (time-averaged data). However, the FR coating exhibited a comparable fouling level without cleaning.

Preventive strategies

Surface modifications are critical in enhancing the antifouling properties of membranes used in water treatment. Fouling, which includes the accumulation of contaminants like organic matter, microorganisms, and inorganic particles, significantly reduces membrane efficiency. Recent studies highlight that surface modification is an effective strategy to mitigate this issue. For instance, modifying membrane surfaces with hydrophilic and antimicrobial coatings can reduce the adhesion of foulants. Techniques such as grafting hydrophilic polymers, incorporating nanoparticles, and using zwitterionic materials have shown promise in improving antifouling performance. These modifications enhance membrane longevity and efficiency by reducing the frequency of cleaning and maintenance required, thereby offering a sustainable solution to water pollution caused by fouling (Yalcinkaya et al., 2020). Hydrophilic coatings can reduce the initial bacterial adhesion, one of the first steps in biofilm development. This can delay or reduce the biofilm buildup, making the system more efficient. However, there is limited research on the long-term environmental impact of hydrophilic coatings. Depending on the material used, they may leach chemicals into the water, potentially developing antimicrobial resistance and harming aquatic ecosystems. Their uncontrolled release can also disrupt microbial communities essential for ecosystem function.

Meanwhile, antimicrobial coatings can directly prevent biofilm formation by killing or inhibiting bacteria upon contact, thus addressing biofilm formation at its root cause. Nevertheless, continuous exposure to antimicrobial agents can lead to the development of resistant strains, especially in bacteria. Over time, this resistance could render antimicrobial coatings less effective. Many antimicrobial agents, especially metals like silver and copper, can leach into the water, potentially contributing to water pollution and having toxic effects on aquatic ecosystems.

Hydrodynamic conditions significantly influence water quality by affecting pollutants' transport, dilution, and distribution. Proper management of these conditions can mitigate water pollution in various aquatic environments. Hydrodynamic factors such as flow velocity, turbulence, and water exchange rates play a crucial role in the dispersion and dilution of contaminants. Studies have shown that increased flow velocities and turbulence enhance the re-oxygenation rate and promote the mixing and dilution of pollutants, thereby reducing their concentration and harmful impacts (Kang et al., 2022; Wei et al., 2024). In urban rivers, managing hydrodynamic conditions involves using real-time data to optimize water flow and reduce pollutant concentrations. For example, constructing artificial structures like dams, reservoirs, and groynes can regulate water flow and create settling conditions that aid in removing suspended solids and other pollutants. These structures can trap contaminants, allowing natural sedimentation processes to occur, effectively reducing the load of pollutants entering downstream ecosystems (Kumar et al., 2021). Increasing water flow velocity and turbulence can create shear forces that physically disrupt the initial adhesion of bacteria, preventing them from establishing biofilms. This is particularly effective in preventing early-stage biofilm formation. High flow rates also reduce stagnation, which minimizes the accumulation of organic matter and other nutrients contributing to biofilm growth. However, maintaining high flow velocities or creating turbulent conditions can require significant energy inputs, particularly in large industrial or municipal water systems. This can increase operational costs and energy consumption, which may not align with sustainability goals.

Removal Strategies

Mechanical techniques for biofilm removal primarily involve the physical disruption and removal of biofilm structures from surfaces. Mechanical scrubbing, high-pressure water jets, and ultrasonic treatment are common methods used in various water systems. Mechanical scrubbing is a traditional and effective method, especially for easily accessible surfaces. This technique physically disrupts the biofilm matrix, making it easier to remove accumulated biofilms. High-pressure water jets use intense water flow to dislodge biofilms from surfaces, providing a non-chemical alternative for cleaning. Ultrasonic treatment employs high-frequency sound waves to induce cavitation, which disrupts the biofilm structure at a microscopic level. These techniques benefit their immediate and effective biofilm removal capabilities, particularly in potable water systems where chemical residues must be minimized (Li et al., 2023). Mechanical scrubbing can effectively remove thick biofilms that are difficult to break down using chemical methods alone. It is especially effective on flat, easily accessible surfaces. This technique produces immediate results, making it useful in emergencies where biofilm buildup is causing operational or safety issues. However, repeated scrubbing can lead to wear and tear on material surfaces, compromising the system's integrity. Scratching or pitting of surfaces facilitates quicker biofilm regrowth by providing more surface area for bacteria to adhere to. High-pressure jets can effectively dislodge mature, well-established biofilms, reducing the risk of further contamination or system blockage. While high-pressure jets can remove visible biofilm layers, microscopic remnants often remain on surfaces. These remnants can act as seeds for rapid biofilm regrowth. Ultrasonic treatment is non-invasive and non-destructive to materials, which makes it particularly useful for cleaning sensitive or delicate equipment. Continuous use of ultrasonic technology may require significant energy, which could be costly and unsustainable for large-scale systems.

Biofilm-degrading enzymes represent a biologically based approach to biofilm control. Enzymes such as proteases, amylases, and cellulases target specific biofilm matrix components. Proteases break down proteins within the EPS, amylases degrade polysaccharides, and cellulases target cellulose. Enzymes are advantageous due to their specificity and ability to operate under mild conditions, reducing potential damage to the underlying surfaces. Recent advancements have focused on optimizing enzyme formulations and delivery methods to enhance their effectiveness in industrial and water treatment applications. Enzyme-based cleaning techniques are increasingly recognized for their environmental friendliness and potential to complement other biofilm control strategies (Liu et al. 2024). Enzymes specifically target biofilm components without damaging the underlying material, making this method highly selective and reducing the risk of material degradation. However, enzymes can be inactivated by environmental conditions such as high temperatures, extreme pH levels, or certain chemicals, limiting their applicability in some water systems.

Oxidation processes utilize strong oxidizing agents to degrade biofilm matrices and kill microorganisms. Common oxidizing agents include chlorine, ozone, and hydrogen peroxide. Chlorine is widely used due to its effectiveness and cost-efficiency. It disrupts the biofilm structure by oxidizing the extracellular polymeric substances (EPS) that hold the biofilm together while killing the embedded microorganisms. Ozone is another powerful oxidant that effectively penetrates and destroys biofilms, making it particularly useful in water treatment applications. Hydrogen peroxide, often combined with other agents, generates reactive oxygen species that degrade biofilms and disinfect the treated surfaces. These oxidative processes ensure comprehensive biofilm removal and prevent regrowth (Roy et al., 2018). Oxidizing agents are highly effective against various microorganisms, including bacteria, viruses, and fungi, making them suitable for various water systems. Prolonged use of oxidizing agents can corrode pipes and other infrastructure, leading to costly maintenance and replacement needs.

Nanotechnology offers transformative solutions for water treatment due to its scalability, versatility, and ability to address a range of pollutants, including biofilm control. Nanoparticles such as silver, titanium dioxide, and carbon-based nanomaterials can disrupt biofilm matrices and enhance microbial inactivation (Yakup et al. 2024) while minimizing chemical leaching. Various nanomaterials, including nano-adsorbents, nanomembranes, and nano-photocatalysts, have shown potential in removing contaminants such as heavy metals, organic and inorganic pollutants, and biological organisms (Khan et al., 2019; Ajith et al., 2021). These nanomaterials possess unique properties, such as high surface area and aspect ratio, which enhance their efficiency in processes like sorption, catalysis, and filtration (Khan et al., 2019). Nanotechnology-based water treatment methods offer improved efficiency, flexibility, and affordability (Theron et al., 2008). However, most research is still confined to laboratory or pilot scale, and further investigation is needed to address potential toxicological effects on humans and the environment. Nanotechnology has great potential for advancing water management and addressing global water challenges.

Future direction

As biofilms pose significant challenges in water systems, addressing their formation and persistence is crucial for mitigating water pollution. Emerging technologies, interdisciplinary research, and innovative approaches provide promising future directions in controlling biofilm-mediated water pollution. Advanced coatings with dynamic properties that respond to environmental stimuli (e.g., pH, temperature, or microbial presence) could help prevent biofilm adhesion. For instance, coatings that release antimicrobial agents when biofilm starts to form or that change surface properties (from hydrophobic to hydrophilic) under certain conditions can inhibit biofilm growth. Nanotechnology can be leveraged to create ultra-smooth surfaces or materials with nanostructures that disrupt bacterial adhesion and biofilm formation (Yakup et al. 2024; Yusri et al. 2024). Self-cleaning or antibacterial nanocomposite coatings (e.g., silver, copper, or zinc oxide nanoparticles) could prevent microbial colonization in water systems. Researchers can design synthetic molecules or engineered microbes that interfere with bacterial quorum sensing, the communication system bacteria use to form biofilms (Naga et al., 2023).

This would prevent biofilm formation at early stages, reducing the need for harsh chemical treatments. Engineering or encouraging beneficial microbial communities in water systems that compete with or inhibit harmful biofilm-forming species could be a natural and sustainable approach to biofilm control (Chakraborty et al. 2017). This approach mimics natural ecological processes where competition and predation regulate microbial populations. Developing biodegradable, non-toxic antimicrobial agents that break down quickly in the environment without producing harmful by-products is crucial. These could include plant-derived antimicrobials, biodegradable nanoparticles, or engineered peptides. Recent research demonstrates the growing application of artificial intelligence (AI) in biofilm monitoring across various sectors. Deep learning models have been developed to automate the analysis of bacterial cell images, significantly accelerating the process of extracting geometric properties from biofilms (Ragi et al., 2021). AI models have also been employed to optimize biocide dosing in industrial processes, considering environmental, technical, and economic factors (García et al., 2024). Future water systems could incorporate biosensors that detect biofilm formation at its earliest stages (Figure 5). These sensors could measure factors such as biofilm thickness, microbial activity, or quorum-sensing molecules, enabling real-time data collection and the prompt activation of biofilm control mechanisms such as releasing an antimicrobial agent or adjusting flow rates (Subramanian et al. 2017).

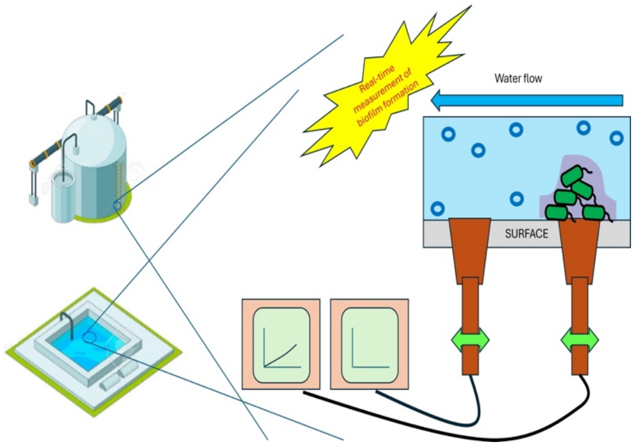

Fig. 5: The application of a biosensor system for real-time detection of biofilm formation in water treatment facilities, enabling efficient monitoring and prevention strategies.

CONCLUSION

Biofilms in water systems pose significant challenges by causing clogs and blockages in pipes, deteriorating water quality, and posing health risks. Addressing these issues requires a comprehensive understanding of biofilm formation and growth and implementing effective prevention and removal strategies. Ongoing research is crucial to developing innovative solutions to manage biofilms and maintain the integrity and functionality of water distribution systems. Additionally, effectively addressing the challenges posed by biofilms in water systems demands integrated solutions that combine advanced engineering, microbiology, and material science to ensure sustainable and long-term outcomes.

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AUTHOR’S CONTRIBUTION

Anati Abd Rashid Syaida conducted the research and wrote and revised the article. Mohd Fakharul Zaman Raja Yahya conceptualized the central research idea and provided the theoretical framework. Rikson Siburian, Mohd Taufiq Mat Jalil, and Mohd Muzamir Mahat anchored the review and approved the article submission.

CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted without any self-benefits or commercial or financial conflicts and declare the absence of conflicting interests with the funders.

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