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A Review on Biofilm-Based Bioremediation: An Innovative Strategy for Sustainable Environmental Management

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Abstract: An increase in environmental pollution as a result of industrial and agricultural operations has displayed an ongoing need for systems that can provide sustainable remediation. This highlights that microbial biofilms have a unique ability to adsorb, transform and degrade various pollutants which led us towards an effective bioremediation approach by using embedded bacterial cells in alginate beads as well as powder feeding bacteria or added sludge also play important role for anaerobic degradation. Biofilms are varied microbial communities that develop within protective matrix in a polysaccharide structure called biofilm extracellular polymeric substance (EPS), g or have been shown to promote survival, interspecies cooperation and resistance towards acute stress condition. This review article summarizes the structure and formation of biofilms with a special focus on major mechanisms involved in their remediation process (biosorption, bioaccumulation, biodegradation, biotransformation and biomineralization) as well as various applications that can be used for heavy metals removing from surfaces or solutions; experiments evaluating hydrocarbons degradations studies began dyes retention followed by pesticides degradation assays into an wastewater treatment system. We also assess bio-engineered improvements, synthetic microbial consortia and innovations in nanotechnology alongside omics methods & artificial intelligence. To sum up, biofilm-based processes are sustainable modalities in environmental control and the application of biofilms has a high potential due to its positive characteristics for enhancing bioremediation.

Keywords: Microbial Biofilms; Bioremediation; Environmental Pollution; Wastewater Treatment; Pollutant Degradation.

Introduction

Environmental pollution is among the most important threats globally as a result of industrialization, urbanization and intensification of agriculture combined with many different anthropogenic practices. Huge amount of contaminants such as heavy metals petroleum hydrocarbons pesticides textile dyes pharmaceuticals and other emerging pollutants (MPs) routinely discharged into

soil water systems. These pollutants, due to their recalcitrance and toxicity with respect to humans, wildlife and ecosystems along with the bioaccumulation potential represent a serious threat towards environmental sustainability, biodiversity as well as for human health. Conventional remediation technologies such as chemical oxidation, precipitation and incineration (e.g.) Physical separation processes, as well as those based on aseptic techniques typically feature low operational cost for contaminant removal but incomplete destruction of the contaminants and generation of secondary pollutants. Therefore, in the current management of environment-oriented development and availability these sustainable brands became more important. [1][2].

Bioremediation is a process that has drawn significant attention as an inexpensive source technology alternative to other technologies because it changes, detoxifies and removes uncontaminated effluents from the environment can be accomplished using microorganisms and their metabolic activities. Microbial communities represent a key factor in natural attenuation and thus can be utilized for bioremediation (including the treatment of contaminated soils/groundwater, industrial effluents or marine environments) processes. Bioremediation, has mainly been studied in association with planktonic microorganisms, yet most natural ecosystems are dominated by bio- films and not free-living cells[3].

Methodology

Biofilms are structured microbial communities adhered to biological or abiotic surfaces, enmeshed within a self-secreted extracellular polymeric substances (EPS)matrix . The EPS matrix mainly contains polysaccharides, proteins (mainly in the early phase), lipids, eDNA and other biopolymers that support stability of bioaggregates as they are embedded into a protective environment. Polysaccharides facilitate the adherence of bacteria to each other and/or surfaces (both biotic and abiotic).Biofilms formed in this way represent one of the most efficient surviving strategies that enables microbes not only survive but also proliferate severely limiting environmental conditions, nutrient deficiency, toxic agents or microbials . It is known that biofilm-associated microorganisms demonstrate a higher metabolism, greater resistance to environmental stressors and ecological superiority in comparison with the planktonic cells .

Biofilms possess specialized structural and physiological properties which makes them particularly appealing yet underused tools for bioremediation. Extracellular polymeric substances (EPS) contain numerous functional groups that allow them to adsorb and immobilize pollutants, while a microbial population permits biodegradation and efficient biotransformation processes. Biofilms also provide the architecture for synergism between different microbial species wherein metabolic cooperation dominates to achieve degradation of complex contaminants. Therefore, some biofilm systems have been used in many areas of application: wastewater treatment processes[4] heavy metals removal hydrocarbon biodegradation[5] and dye decolorization or other pollutants remediation from industrial effluents.[6][7]

New technologies in molecular biology, synthetic biology, omics (metagenomics), nanotechnology and artificial intelligence have dramatically increased our ability to study biofilm dynamics and its potential environmental biotechnological applications [8][9][10][11][12]. Traditional remediation technologies have beneficial effects but still, they are not without limitations. Despite these advances, numerous challenges persist which require solutions to deliver all the anticipated benefits of this technology on a case by case basis such as biofilm detachment[13] mass transfer limitations within reactor systems [14][15] >Table S2 and there is an additional need for continuous optimization in combination with scale up using novel bioreactor designs under dynamic environmental conditions.

Hence, in the present review we intend at discussing effect of biofilms on bioremediation that actually cover multiple aspects including its formation and structural characteristics; mechanisms for pollutant removal along with environmental applications. We also critically discuss recent advances in biofilm technology, extant challenges and future prospects of biofouling-based bioremediation approaches to highlight their potentials in sustainable pollution management.

Results and Discussion

Structural and functional core of biofilms

Biofilms are called complex microbial communities that adhere to biotic or abiotic surfaces and surrounded with a self-producing extracellular polymeric substances (EPS) matrix. In contrast, biofilm-associated cells are generally more resistant to environmental stress due (in many cases) their structural organization but also show increased capability for nutrient utilization and higher survivability. Previous research shows that these qualities make biofilms a powerful system for environmental bioremediation[16].

Biofilms can be observed through a series of sequential associations: initial adhesion, irreversible attachment (through the movement and growth²¹), mature biofilm – as they grow into multilayer structures¹⁸; loose or dispersed cells. The primary attachment is mediated by different physicochemical interactions based on environmental factors like surface properties, nutrient availability and pH/temperature. Then, EPS leads to cell anchorage on surfaces as well as biofilm structural stability

During the maturation of biofilms, microcolonies are generated and water channels form in microbial cells to distribute nutrients & remove waste. EPS, which accounts for a majority of total biofilm biomass mainly consists of polysaccharides, proteins and lipids as well as extracellular DNA (eDNA). This includes contributions to biofilm integrity, communication between the microbes and protection against environmental stresses.

Biofilm development is regulated by quorum sensing, a cell density-dependent form of communication that coordinates EPS production and biofilm maturation while repressing motility and the induction of enzymes related to degradation. The synchronized action increases the metabolic efficiency and degradation of pollutants, compared to free-living microorganisms.

The EPS matrix also serves as a shield against extreme conditions, such as toxic chemicals, heavy metals, salinity and oxidative stress. Also, it enhances microbial cooperation by enabling the exchange of nutrients, metabolites, signaling molecules and genetic material between distinct microbes. These types of interactions promote the emergence of metabolically diverse consortia possessing enhanced capacities for hydrocarbon degradation in situ.

In general, the EPS matrix is the functional core of biofilm playing roles in structural support and environmental protection including pollutant adsorption along with increased cooperation among microbial population. It is these integrated properties that provide the basis for biofilms being such effective agents in bioremediation applications and demonstrate their potential benefit to sustainable environmental management.[17]

Mechanisms of Biofilm-Mediated Bioremediation

One of the key reasons that biofilms can effectively remediate contaminated environments is due to their ability for synergistic pollutant removal mechanisms take places concurrently. Unlike planktonic microorganisms, biofilm-associated communities can utilize high density of microbes [18] thereby may produce extracellular polymeric substances (EPS) by constituent organisms or intercellular metabolic cooperation and multi-stress resistance , leading to a series of biologically and physicochemical coupled phenomena which could act as modulators for very large range removal efficiency, detoxification kinetics rate or transformation rates. The following are the primary mechanisms governing biofilm-mediated bioremediation: biosorption, bioaccumulation, biodegradation (target-specific microbial degradation), and also interaction of bacteria with heavy metals or organic compounds through a series of metabolic pathways called biotransformation and biomineralization.

Biosorption

Biosorption is a type of passive physico-chemical process where adsorption occurs on microbial cell surface and in matrixes made up by extracellular polymeric substances. It is considered as one of the fastest and most efficient mechanisms linked to biofilm-based remediation processes, especially in abnormal removal for metals pollutants or any other ionic pollutant. EPS matrix is contain rich functional groups such as carboxyl group, hydroxyl group, phosphate group and amino acid residues , which can provide many sites for binding pollutants molecules.

Adsorption can occur due to different mechanisms, such as ion exchange electrostatic capture complexation chelation and hydrogen bonding, among others. The high molecular weight ions of metals like lead, cadmium, chromium and copper present in environment can readily bind with the negatively charged groups available in EPS matrix resulting the immobilization without any change of mobility for these contaminants during contaminated areas. Since biosorption is not dependent on the metabolism of cells, both living and non-living biomass may play a role in pollutant removal. This property makes biosorption at least highly attractive for the treatment of wastewater from industries containing high concentration of toxic metals.

Bioaccumulation

In contrast to biosorption, bioaccumulation is the active metabolic process whereby viable microorganisms uptake and then physiologically sequester contaminants intracellularly. When pollutants adhere to the biofilm surface, they can transfer across cell boundaries and then enter the cytoplasm. Despite the fact that cationic and anionic compounds exert concentration-dependent effects, they are primarily mediated via cellular mechanisms involving selective transport proteins or detoxification systems. Contamination by heavy metals, radionuclides and various organic compounds are a significant source of reversibility in bioaccumulation. Microorganisms can either sequester these toxic compounds in intracellular compartments or transform them to less harmful forms via enzymatic reactions. The results can be improved by simultaneously analysing spectral data modes but this increases the time for sample analysis and has a restriction that high biomass densities are characteristic for matured biofilms, which is also separating overall better contaminants from water than classical methodology. EPS matrix provide a niche that protects microbes against toxic pollutant concentration, which would otherwise be inhibitive for planktonic cells.[19].

Biodegradation

Biodegradation is one of the most significant mechanisms involved in biofilm-mediated bioremediation. This is done through the anaerobic degradation of large organic pollutants to small and less toxic molecules, which can be used as sources of carbon and energy by microorganisms. Microorganisms associated with biofilm are known to produce a variety of extra- and intracellular enzymes[20] which can breakdown different environmental pollutants. Hydrocarbons, pesticides, pharmaceutical residues and phenolic compounds as well synthetic dyes are the most frequency degraded pollutants. 1.3 Biodegradation and Key Enzymes: These enzymes may include contributing factors such as oxygenases, monooxygenases, dioxygenases (involving two molecular oxides), dehydrogenase (+ oxidation reaction), laccase & peroxidises etc.,[24:283299 hydrolästoppers.

Biotransformation

Biotransformation is the process through which pollutants are modified by biological enzymes into forms that have been chemically altered and reduced toxicity or mobility, increased biodegradation potential. Biotransformation is not a complete mineralization of all the contaminants, but leads to transformation and intermediate products that have less negative impact on environment relative they are called degradation (Hayat et al. It's involved in heavy metal and xenobiotic compounds bioremediation. For example, some microorganisms have the ability to passively reduce toxic hexavalent chromium (Cr(VI)) into less-toxic trivalent form. Similarly, chlorinated hydrocarbons pesticides and pharmaceutical residues can be converted to products with lower toxicity by microbial enzymes probably enhancing the susceptibility of these molecules to further degradation. The coexistence of aerobic and anaerobic microenvironments within biofilms facilitates diverse transformation reactions to occur simultaneously, enhancing remediation efficiency[21].

Biomining

Biomining is a biological reaction which may result in an increase of insoluble mineral forms from dissolved contaminants. Ceramic materials, in particular Phosphate Bonded Ceramics (PBC) have been accepted as inert hosts for long-term storage of heavy metals and radionuclides. Biofilm microbes can modify local physiochemical conditions (for example, pH, redox potential and ion concentrations), enhancing the precipitation of minerals.

Biomining processes are a consequence of multiple metabolic activities. One of these is sulfate-reducing bacteria which can produce sulfide ions that react with dissolved metal cations to

create small insoluble groups called phosphors. Likewise, ureolytic microorganisms can mediate carbonate precipitation and metal immobilization in the solid-state form of carbonate minerals. The EPS matrix also helps mineral nucleation by creating reactive sites that bind to crystals so they can form and grow

Biomining is a promising alternative for environmental remediation, as it transforms mobile contaminant phases into stable solid counterparts capable of remaining passive within the environment. This procedure mitigates the chance of pollutant movement and reduces prospective impacts on humans as well. This led to a growing interest in biomining as a sustainable method for the remediation of heavy metal contaminated soils, sediments and industrial wastewaters

In a combined action, biosorption, bioaccumulation (to some extent), biodegradation biotransformation and biomining work together in the role of biofilm systems to remove pollutants efficiently. The structural and functional complexity of biofilms, combined with these mechanisms helps explain their higher efficiency in a variety of environmental remediation applications. To further optimize biofilm-based technologies or develop new, more efficient strategies for pollution control in a sustainable way these mechanisms must be understood.

Biofilms in Heavy Metal Remediation

The extensive spread of industrial, agricultural, mining and urban activities globally means heavy metal pollution is among the most serious environmental issues[22]. Unlike the organic pollutants, most of heavy metals are persistent in natura and non-biodegradable elements making them serious threats to ecosystems microbes as well humans health (see table 1. Non-essential heavy metals (HMs) such as Lead Pb, Cadmium Cd, Chromium Cr, Mercury Hg Copper Cu Nickel Ni Arsenic As and Zinc Zn that can be bioaccumulated in food chains are able to induce toxic effects on living organisms even at lower concentrations. Therefore, the development of environmentally friendly and effective methods for removing heavy metals from effluents in environmental remediation has become urgent.

Table 1. Toxicity of heavy metals to microorganisms[23]

Heavy Metals	Effects on Microbes
Arsenic	Deactivation of enzymes
Cadmium	Denature protein, destroy nucleic acid, hinder cell division and transcription
Chromium	Growth inhibition, elongation of lag phase, inhibition of oxygen uptake
Copper	Disrupt cellular function, inhibit enzyme activities
Selenium	Inhibits growth rate
Lead	Destroyed nucleic acid and protein, inhibit enzyme actions and transcription
Mercury	Denature protein, inhibit enzyme function, disrupt cell membrane
Nickel	Upset cell membrane, hinder enzyme activities and oxidative stress
Silver	Cell lysis, inhibit cell transduction and growth
Zinc	Death, decrease in biomass, inhibits growth

One of the most efficient systems to remediate heavy metals can be advanced by microbial biofilms which exploit their structural and functional characteristics. Since the EPS matrix is passive and the principal interface for metal contaminants, it contains a great number of reactive sites which are able to bind metals. In addition, they promote metal accumulation and increase transformation by implementing high density bio films. Biofilm-based bioremediation systems are a potential new class of oil spill treatment technologies with more environmental relevance compared to traditional physicochemical treatments methods, as biofilms can be pre-programmed for continuous operation and often use less costly resources over prolonged periods in various environments.

Biofilms have distinct resistance mechanisms for heavy metals like passive biosorption, active bioaccumulation and also biotransformation and biomining processes other than the extracellular sequestration . Among all these mechanisms, biosorption is widely regarded as the primary mechanism affected in early metal removal (Moss et al. As far as we know all the carboxyl,

hydroxyl and amino phosphate and sulphydryl groups in EPS matrices are able to interact with dissolved metal ions by combining electrostatic attraction ion exchange or type of complexation reactions. These processes decrease metal mobility and bioavailability, thereby mitigating risk.

Biofilms with fewer than 14 or mixed-species biofilm solution can mediate heavy metal remediation by utilizing this characteristic cooperatively more efficiently, due to their shown higher resilience against the toxicity of metals resulting from lower relative metabolic diversity compared to their loads. And with the consecutive developments of biofilm engineering, synthetic biology and nanotechnology it has ameliorated metal-binding capability and remediation efficiency.

The removal efficiency of heavy metals is also affected by biofilm composition, environmental conditions and properties of metal. In essence, biosorption is required at the very beginning of treatment; while biofilm adhesion and active metabolism under trace metal exposure determines long-term performance. However, most of them are still limited to laboratory scales studies; and a field-scale implementation is just another challenge. Ultimately, experimental studies should therefore focus on the long-term stability of scale-up and performance of biofilm systems under more realistic environmental conditions[24]. Conclusion Biofilms with native and engineered microbial communities serve as an eco-friendly vehicle for biologic processes similar to physical immobilization of heavy metals (adsorption), metal recovery through cell lysis (accumulation or transformation) while providing multiple functions including impregnating soils/water columns.

Biofilms in Hydrocarbon Bioremediation

Hydrocarbons represent a huge class of compounds: aliphatic hydrocarbons, aromatic hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), Resins and asphaltenders; adding various toxic derivatives. Petroleum hydrocarbons appear to be among the world's most widespread environmental contaminants and are released into soil, water and air through oil spills, petroleum production processes or gas stations. Hydrocarbon pollutants are wide-spread and persistent environmental contaminants that pose major threats on terrestrial/ aquatic ecosystems, biodiversity & ecological functions together with human health. Hence, design of adequate remediation strategies to restore hydrocarbon-polluted site is a hot research topic in Environmental biotechnology. Due to their complex structure and resistance to biodegradation [25] polycyclic aromatic hydrocarbons (PAHs) pose a major challenge.

Microbial degradation is well known to be the most effective and eco-friendly way for hydrocarbon removal. In natural ecosystems, hydrocarbon-degrading microorganisms generally occur as biofilms attached on soil particles, sediments, rocks and aquatic surfaces from "oil monolayers". Biofilm formation can activate microorganisms because they provide structural stability and shield from toxic impedances due to the hydrophobic nature of substrates such as hydrocarbons, therefore increasing their physiological power through improved access efficiency (fast plant solubilization).

The key benefits in biofilms being advantageous over planktonic suspension for hydrocarbon bioremediation include a closer association of microbes with insoluble hydrocarbons. The low water solubility and poor bioavailability of many petroleum compounds often inhibits microbial degradation because there is insufficient useable substrate. In this way, the EPS matrix was able to adsorb and retain hydrophobic compounds for biofilm microenvironment concentration of pollutants. This localized accumulation as well as higher substrate availability should render biodegradation processes more efficient.

Biosurfactant Matrix Formation Biofilm. Biosurfactants play an important role by improving the solubility, emulsification and bioavailability of hydrocarbons for microbial uptake and metabolism. Both biosurfactants and EPS create a favorable environment for hydrocarbon degradation in biofilm consortia. Aerobic hydrocarbon degradation is initiated by biofilm-associated microorganisms using enzymes such as monooxygenases and dioxygenases, with subsequent oxidation of the resulting intermediates through classical central metabolic pathways to mineralization to carbon dioxide + water. Transacting alternative electron acceptors include nitrate, sulfate and ferric iron which support anaerobic degradation under oxygen-limited conditions. Mature biofilm contains both aerobic and anaerobic microenvironments, which serve as the means by which microbial communities degrade contaminants for their removal.[26].

Biofilms in Wastewater Treatment Technologies

Municipal, Industrial and Agricultural Wastewater consists of various contaminants including organic matter, nutrients (N & P), heavy metals, dyes and pharmaceuticals as well as pathogens due to the food-processing etc. Along with increased complexity of waste water, there is a growing demand for effective and sustainable treatment technologies. Biofilm-based systems became up-to-date techniques because of operational stability, internal bio-mass retention, resistance to poisonous compounds and effective pollutant removal. These are based on attached microorganisms to solid surfaces forming dense and diverse communities that can perform multiple metabolic processes. Owing to these features, biofilm reactors exhibit better selection from a diversity of microbes for contaminant removal than that in conventional suspended-growth systems as well as do not generate sludge or produce less and cope with environmental fluctuations.[27].

The trickling filter is a biofilm-based wastewater treatment technology in which the flow of wastewater passes through an inert packed bed that provides surface area for biofilm growth. In this bioreactor, the biofilm degrades organic contaminants as well as nutrients and oxygen is supplied by either natural or forced aeration. Trickling filters are simple, robust, energy-efficient and in widespread use worldwide[28].

Rotating biological contactors (RBC) are rotating discs that partially submerged in wastewater to allow biofilms the alternating access of wastewater and atmospheric oxygen. This improves oxygen transfer and biodegradation, but also efficiently removes BOD (biological demand) and ammonia with low energy input. Their attached-growth configurations also provide resistance to hydraulic and organic shock loads.

MBBRs feature freely-flowing carrier material in an aeration or mixing tank that supports the development of biofilms. Carrier motility enhances mass transfer and maintains elevated active biomass concentrations. MBBRs combine the best of both attached- and suspended-growth approaches while being effective for removal of organic pollutants, nitrogen, phosphorus and other industrial contaminants at a high treatment capacity with operational flexibility[29][30].

The rapid development of synthetic biology has made it possible to encode simple biofilms that sense some environmental signals and leverage pathways involved in targeted metabolic activities when its pollutants are present. Biosensor-based biofilms can detect and degrade contaminants in parallel, allowing for real-time monitoring and enhanced remediation efficiency [31].

Although these biofilms are promising, there still exist challenges related to genetic stability of the inserted genes, competition with native microorganisms in natural environments or during their delivery and horizontal gene transfer that prevents using suitable engineered consortiums for bioremediation purposes; additionally environmental safety could be an issue as well leading regulatory agencies to establish stringent regulations on releasing genetically-modified organisms into ecosystems. Environmental variability and complex interactions with the microbial communities can also limit their long term efficiency.

Emerging omics, computational modeling technologies and artificial intelligence can assist in the rational design of biofilm systems by predicting microbe-microbe interactions within built environments to optimize composition as well as identifying crucial microbial degradation pathways. Combining these strategies with synthetic biology also promises to enhance the effectiveness, sustainability and safety of future biofilm-based bioremediation technologies. In summary, we believe the combination of Synthetic Biology & Omics AI holds great potential to generate engineered biofilms equipped with precisely regulated but highly adaptable and sustainable platforms for efficient remediation (bioremediation) applications targeting complex environmental pollutants therein in a Programmable Biomanufacturing manner.

Biofilm-Based Removal of Dyes and Pesticides

Industrial and agricultural practices extensively utilize synthetic dyes & pesticides, thus renders it highly polluted on the ecological front. The release of waste products from textile, the manufacture of paper (involving tanning but all are processed for other purposes: cosmetics or food system x Biodiversity) into nature scenery; Land art overwrought this out! Persistent Environmental Contaminant Due to their complex chemical structure, synthetic dyes and pesticides have a high

stability in the natural environment which tactics them as resist of nature-inspired degradation mechanism. The accumulation of these in aquatic and terrestrial environments, indeed bioregional environmental chemistries acting on microorganisms plants animals to humans life. So there is a growing need for the economy to support habitat protection initiatives like soil and. water further downstream one of many fundamental goals are escalating resilient green remediation connected technologies

Consequently, microbial biofilm has received particular attention as consortia biological systems were implemented for the removal of organic dyes and pesticides. Various mechanisms of multitasking remediation can go together with the help of structural complexity, metabolic diversity and pollutant binding through biofilms. That includes the adsorption and biodegradation biotransformation processes resulting in synergistic facilitation of mineralization process leading to increased efficiencies of contaminants removal. I am much more resistant to pollution conditions than those free living planktonic microorganisms and I have a high level of activity even under contaminated situations. [32][33].

Engineered and Synthetic Biofilms

Natural biofilms represent a class of highly applicable biological systems for environmental remediation, but their relatively slow degradation rates and sensitivity to changes in various ecological parameters (e.g., nutrient limitation or temperature) as well as competition dynamics among microbes limit their application. Synthetic biology, genetic Engineering systems biology and microbial ecology advances can maybe facilitate to design biofilms engineered specifically with capabilities that bypass the limitations mentioned above in order smooth specific targeted bioremediation[34]. Engineered biofilms are engineered or genetically modified microbial communities with enhanced functional capabilities, such as pollutant degradation activities (MSCE), heavy metal binding capacity, production of biosurfactants and stress resistance . This work provides new information on the biogeochemical cycling of elements by microorganisms and also aids in removing recalcitrant pollutants that are not removed efficiently via natural biodegradation processes. One major advantage of engineered biofilms is heightened pollutant degradation by means of metabolic optimization. Such genetic modifications may increase production of the enzyme needed for biodegradation, improve substrate utilization efficiency (in case there are other more easily accessible substrates) and decrease toxic metabolite accumulation during biodegradation. Moreover, metabolically active microorganisms can be adapted to extreme environmental conditions (i.e., high salt and temperature stability), acid resistance as well as elevated concentrations of toxic contaminants that may contribute to improved biofilm stabilization during bioremediation. Quorum sensing engineering represent a versatile tool to improve biofilm activity by modulation of EPS production, cellular motility during maturation or dispersal and expression levels of enzymes. Increase in the cooperation and degradation of pollutants involving engineered biofilms that require manipulation through synthetic communication circuits or natural pathways (quorum sensing).

However, the implementation of these advances in practice is still limited by hurdles such as genetic stability, ecological safety, microbial competition and regulatory acceptance. Most studies have employed controlled lab conditions, but the behavior of engineered biofilms in native ecosystems remains poorly characterized. Synthetic biology, coupled with artificial intelligence and systems biology can provide additional avenues of opportunities for the development of efficient biofilm consortia; however standard assessment frameworks remain a necessary tool in understanding their environmental performance.[35].

Future perspectives

Recently, biofilm-based bioremediation has represented an efficient ecofriendly alternative to much-contaminated ecosystems remediating techniques because of its enhanced stability and resilience as well as pollutant degradation efficiency. Though progress has been made, challenges still remain that need to be resolved for large scale adoption and the full realization of its environmental benefits.

Future works should be directed toward the establishment of adjusted engineered and synthetically assemble biofilm consortia with specific metabolic forms to biotransform complex arising contaminants, comprising pharmaceuticals or microplastic like endocrine disruptors as well as non-

biodegradable organic pollutants. The recent advances in synthetic biology metabolic engineering and the genome-editing technologies pave a new way to design microbial communities with improved biodegradation performance under extreme environmental conditions. Although several technologies exist today, the implementation of omics techniques—genomics, transcriptomics, proteomics and metabolomics[36]—will allow for improved understanding of biofilm structure and function as well elucidating microbial interactions in a variety of environmental settings. This knowledge would help identify the major functional genes and metabolic pathways associated with pollutant degradation, which can improve biofilm-mediated remediation systems via optimization .

A yet more interesting approach lies in the combination of nanomaterials and novel materials with biofilm-based systems. By increasing the contact of microbe with biomaterials or by optimizing important physical processes including biofilm thickness, density and porosity, bioremediation performance (both volumetric absorption as well as surface adsorption) could get enhanced. Moreover, the use of biofilm carriers with immobilization matrices based on biodegradable and renewable materials might favor sustainable and cost-effective field applications. Artificial intelligence (AI), machine learning, and predictive modeling tools will also play an important role in transforming biofilm-based bioremediation . These technologies can help in monitoring biofilm dynamics, predicting remedial outcomes for contaminated sites summary defining optimal operational parameters but also enabling real-time management of bioremediation treatments in less favorable environmental conditions.

Last but not the least, it will need a multidisciplinary, well-coordinated effort among microbiologists, environmental engineers and material scientists to be able to commercialize biofilm-based bioremediation technologies into large-scale ecofriendly restoration methods with applications for industry stakeholders as well .Policy Opportunities In summary, ongoing developments in both technological innovation and microbial biofilm ecology are likely to establish biofilm-based bioremediation as a foundational technology underpinning sustainable environmental stewardship and ecosystem restoration during the next decades.

Conclusion

Biofilms as a Model Stable Microbial System Biofilms are among the most recognized stable microbial systems with great potential in environmental bioremediation due to their ability and effectiveness on sorption, conversion and degradation of many organic/inorganic pollutants. They have exciting potential as sustainable environmental remediation tools highlighted by their many uses in heavy metal removal and detoxification of pollutants (e.g. hydrocarbons), wastewater treatment etc Coupling these strategies will greatly enhance their efficiency in a range of bioremediation applications, and biofilm-based bioremediation approach is expected to be developed as one of the realistic tool for environmental management technologies in the future.

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