Microbial exopolymers for soil restoration and remediation: current progress and future perspectives

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Abstract. Soil degradation and pollution are pervasive global challenges caused by climate change and anthropogenic activities. To address these issues, seeking environmentally friendly and sustainable solutions to restore degraded soils and remediate polluted ones is imperative. One promising avenue lies in the utilization of microbial exopolymers, which can play a pivotal role in rejuvenating soil health by enhancing its physical, chemical, and biological properties. Microbial exopolymers, through their various functional groups, facilitate interactions that bind soil particles together, thereby promoting soil aggregation and immobilizing soil pollutants. Thus, the application of exopolymers holds the potential to enable soils to continue providing its essential ecosystem services. Despite significant progress in evaluating the impact of microbial exopolymers on soil properties, there remains a pressing need to overcome existing challenges that hinder the large-scale use of microbial exopolymers for soil restoration and remediation. The significant challenges include (i) inadequate understanding on the effectiveness and safety of exogenous microorganisms and their interactions with native soil biotic and abiotic factors, (ii) the lack of feasible methods for characterizing the constituents of exopolymers produced by soil microbial community, (iii) insufficient efforts in exploring the community diversity of soil microorganisms capable of producing exopolymers in various soils, and (iv) inadequate effort on aligning the molecular characteristics of exopolymers with the specific application purposes. To harness the full potential of microbial exopolymers, interdisciplinary approaches are paramount in achieving improved effectiveness of soil restoration and bioremediation endeavors, which are of utmost importance in the ever-changing environment.

Keywords: soil aggregation, soil microbial EPS, soil bioremediation, soil health

1. Introduction

1.1 Background on soil degradation and pollution

Land, inclusive of its water bodies, serves as the foundation for human livelihoods and well-being by supporting primary productivity, the provision of food, freshwater among other ecosystem services [1]. However, human activities, in conjunction with climate change-related events, are leading to land deterioration and biodiversity loss on our planet [2], [3]. According to the Intergovernmental Panel on Climate Change, land degradation is defined as “a negative trend in land condition, caused by direct or indirect human-induced processes including anthropogenic climate change, expressed as long-term reduction or loss of at least one of the following: biological productivity, ecological integrity or value to humans”. Failing to address land degradation will result in increased emissions and reduced carbon sinks, which is inconsistent with the emissions reductions required to bring global warming to 1.5°C or 2°C [1].

The Food and Agriculture Organization defines soil degradation as “a change in the soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries”. Soil health – characterized by its functionality and ecological
The physical health of soil can be damaged due to various factors like soil erosion (induced by both water and wind), mining, and deforestation. Desertification, a form of land degradation in drylands, including arid, semi-arid, and dry sub-humid regions, results from numerous factors, including human activities and climatic variations. The extent and severity of desertification have increased in some dryland areas over the past few decades, with projected risks of intensifying due to climate change [1]. Another form of soil health degradation is soil pollution. Soil pollution refers to a toxic chemical or substance in the soil at higher-than-normal concentrations, which have adverse effects on any non-targeted organism [5]. Soil pollution typically results from exogenous sources such as chemical fertilizers, pesticides, and oil spills — can result in reduction of both soil chemical and biological health processes. Soil pollution can directly impact human health and severely degrade major ecosystem services that soil provides [5].

To achieve the Sustainable Development Goals of the United Nations, the development and implementation of environmentally friendly technologies are essential to remediate the polluted soils and restore the degraded soils. Conventional methods are not always accessible for low-income countries, or they generate another environmental problem in the long run [6]. Bioremediation, on the other hand, involves the degradation of hazardous pollutants to nonhazardous substances using biological agents. Various microbial mechanisms enable breakdown, transformation, and stabilization of various pollutants [7]. However, when restoring disturbed soils or soils affected by desertification, it becomes imperative to employ techniques that can simultaneously restore the soil’s physical, chemical, and biological properties. Thus, developing microbial technologies tailored to meet these multifaceted soil restoration requirements is of utmost importance.

1.2 Significance of microbial exopolymers in soil health

Soil microorganisms play a vital role in the cycling of soil organic carbon and nutrients. They both produce and consume greenhouse gases, making them central to climate regulation [2], [8]. These microorganisms offer a range of ecosystem services, including providing essential resources, regulating factors such as climate, water, and decontamination, and the support of critical processes like organic matter transformation, soil formation, and plant growth [9]. The structure of soil is a key determinant of its ability to perform these functions effectively. Soil structure is formed by arranging soil particles into aggregates and associated pore networks. The soil aggregates represent the foundational units of soil structure. These units define the soil’s critical physical and mechanical properties, including water retention, water movement, aeration, and temperature regulation. These properties, in turn, profoundly impact the physical, chemical, and biological processes occurring in the soil [10], [11].

A recent global-scale meta-analysis has highlighted the significant contributions of soil bacteria and fungi in soil aggregate formation. Bacteria have a substantial impact on both macro and micro-aggregates, whereas fungi predominantly influence macro aggregation. They contribute to soil aggregation through various mechanisms [3]. One of the mechanisms is the production of exopolymers by soil microorganisms. Exopolymers promote soil aggregation, acting as a binding agent at the micrometer scale. Therefore, microbial exopolymers have garnered considerable attention as an eco-friendly approach to soil remediation and restoration.

1.3 Objectives of the review

Application of microbial exopolymers in various industries, including food, medicine, textiles, cosmetics, and environmental fields have been well documented [12]–[16]. Moreover, several reviews have provided comprehensive insights into the functional roles and biosynthetic pathways and genetic regulations of microbial exopolymers [17]–[20]. However, utilization of microbial exopolymers in soil bioremediation and restoration remains relatively underexplored, primarily due to the challenges associated with investigating the interactions of microbial exopolymers mixture in natural environments [21]. Despite these difficulties, numerous research articles have reported the positive impact of microbial exopolymers on soil health. In this review, we focus on elucidating the mechanisms by which microbial exopolymers enhance soil health, encompassing physical, chemical, and biological aspects. First, we provide a brief overview of microbial exopolymers’ composition, biosynthesis, and functional roles. Subsequently, we present a summary of the current state of knowledge regarding the potential applications of microbial exopolymers and the microorganisms responsible for their production in two key areas: (i) the restoration of soils that have been degraded, (ii) the
remediation of soils contaminated with heavy metals and xenobiotics. Lastly, we conclude by discussing the existing challenges and outlining future research directions in microbial exopolymers for soil restoration and remediation.

2. Soil microbial exopolymers: An overview

2.1 Definition and functions of soil microbial exopolymers

Early research mainly focused on polysaccharides, but it has become clear that proteins, nucleic acids, and other compounds also significantly contribute to composition of microbial exopolymers or extracellular polymeric substances (EPS) [22]–[26]. This section is dedicated to introducing the major components of microbial EPS found in soil, namely polysaccharide and protein. This is because the following sections will be focusing on discussing the potential application of EPS as a whole or its polysaccharides and proteins. The term ‘EPS’ can sometimes be confused with exopolysaccharides. Throughout this review, we will use the term ‘EPS’ to refer to a mixture of polymeric substances secreted by microorganisms into their surrounding environment. When available, we will define the specific constituents of EPS as EPS-polysaccharides or EPS-protein.

2.1.1 EPS-polysaccharides

Polysaccharides constitute a substantial part of biofilm matrices, serving crucial functions in microbial communities. Microbial polysaccharides fall into two main categories: homopolysaccharides, composed of a single monosaccharide unit, and heteropolysaccharides, consisting of multiple monosaccharides, with heteropolysaccharides being the dominant type [27]–[30]. Different microorganisms produce various polysaccharides with distinct structure and composition. Some microorganisms produce a single type of polysaccharide, whereas others produce more than one polysaccharide with different structure and function. Pseudomonas aeruginosa, for example, secretes various polysaccharide types, including alginate, Pel and Psl, each contributing to different stages of biofilm formation, where alginate enhances mechanical stability, while Pel and Psl contribute in biofilm establishment and surface adherence [31]. Analytical methods for structural elucidation of exopolysaccharides extracted from individual microbial isolates are well established [32]. However, direct analysis of soil-extracted EPS-polysaccharides remains challenging due to their low abundance in soil and difficulties related to their purification and characterization.

2.1.2 EPS-protein

Identifying and characterizing soil proteins are challenging due to their interaction with humic acid and soil matrix [33]. The major extracellular protein in soil is a glomalin-related soil protein (GRSP). Although their origin remains dubious, GRSP represents an important group of EPS. Most research seem to agree that arbuscular mycorrhizal fungi secrete GRSP [34]–[38]. However, it was suggested that these proteins could be secreted by free living bacteria [39]. A proteomic technique revealed that glomalin might be thioredoxin-containing chaperon, and not be mycorrhizal origin. The authors detected large amount of soil-related heat stable proteins and protein of non-mycorrhizal origin in GRSP [40]. It was suggested that GRSP fraction could represent soil microbial EPS more than glomalin. Redmile-Gordon et al. [39] proposed the cation exchange resin as the most suitable method to extract soil microbial EPS, with less humic acid contamination and intracellular components. Soil microbial EPS extracted with this method contains both EPS-polysaccharide and EPS-protein. The ratio of the two components vary depending on environmental variables [39], [41]–[44].

2.2 Functions of soil microbial exopolymers

EPS production by microbes is a resource-intensive and energy-demanding process. Thus, EPS confers competitive advantages for soil microorganisms by enhancing quorum sensing and adhesion [45]. EPS also can preserve carbon and trap nutrients for microbial uptake. Additionally, EPS serves various functions, mostly centered around protecting the producing microorganisms from a range of abiotic stresses such as drought, temperature and pH extremes, salinity, and oxidation, and exposure to soil pollutants such as heavy metals and xenobiotics [10]. For example, samples collected from Arctic Sea ice have revealed notably high concentrations of EPS, which act as a shield for microorganisms, protecting the harsh environmental conditions experienced during the winter season. Exopolymers produced by Bacillus sp. strain B3-72 and Geobacillus tepidamans V264 exhibit resistance to dissolution at elevated temperatures [46]–[48]. Additionally, EPS enhances the transfer of genetic material and improves microbe-host (plant) interactions [10]. For instance, EPS play a crucial role in symbiosis between nitrogen-fixing rhizobia and plants [49]. It has been demonstrated that plants can recognize the structure of EPS produced by rhizobia. The interaction between the EPS of Mesorhizobium loti strain R7A and Lotus japonicus was recently shown to be mediated by a receptor expressed by the plant. L. japonicus produces a receptor that binds to and permits infection by only bacteria
that produce EPS with a specific structure [50], [51].

3. Applications of microbial EPS in soil restoration

While synthetic polymers are proven effective in enhancing soil properties, they suffer from low or no degradation in nature and can release potentially toxic compounds into the environment. In contrast, microbial EPS represents an environmentally friendly alternative to traditional chemical polymers due to its exceptional biodegradability, cost-effectiveness, and non-toxic nature for both humans and the environment [10], [15], [52]–[55]. Various biopolymers have been utilized in soil restoration to improve its physical, chemical, and biological properties and enhance the bioremediation efficiency of both organic and inorganic pollutants [56]. In the following section, we aim to categorize current findings regarding how microbial EPS influences soil health by impacting its physical, chemical, and biological properties (Fig. 1).

3.1 Role of microbial EPS in enhancing soil physical properties

3.1.1 Soil aggregating agent

Although microbial EPS has been known for their ability to associate with soil minerals and promote soil aggregation since 1990s [57], [58], researchers’ interest in the role of EPS for soil health has only recently increased. This can likely be attributed to their recognized importance in protecting soil organic matter. A recent study, using high-resolution X-ray computed tomography, confirmed that EPS and mucilage connect soil particles that did not break apart upon drying due to their properties such as high viscosity and low surface tension [59]. Currently, researchers seem to support the idea that EPS-producing microbes or extracted EPS can be used to enhance soil aggregation in degraded soils.

Several researchers have reported a positive correlation between soil EPS content and soil aggregate stability [42], [60]–[62]. Microcosm and pot experiments have demonstrated that EPS-producing microorganisms promoted soil aggregation and increased aggregate stability. For instance, *Pseudomonas chlororaphis* A20 and *Bacillus proteolyticus* A27 were found to increase water-stable macroaggregates in silt clay loam soil [63]. In another study, acid-tolerant *B. amiloliquefaciens* p16 provided acid tolerance to the bacteria while promoting soil aggregation [64], although the soil type used in this research was not specified. EPS produced by *Microbacterium arborescens*, a bacterium associated with a sand dune plant, demonstrated the ability to enhance aggregation in sandy soil [65]. Inoculating two indigenous cyanobacteria, *Nostoc ellipsosporum* HH-205 and *Nostoc punctiforme* HH-206 improved soil aggregate stability in salt affected area [66]. It seems that EPS-producing microbes can propagate in various soils and improve soil aggregation.

Researchers have also explored the relative contribution of EPS constituents in enhancing soil aggregation. Rather than total SOC, EPS-polysaccharide and EPS-protein were correlated with soil structural stability, but EPS-protein was more closely related to aggregate stability than EPS-polysaccharide [42]. Another research reported that EPS-polysaccharide did not correlate with aggregate stability in soil with and without labile substrate addition, whereas EPS-protein showed a positive correlation [67]. It was suggested that the hydrophobicity of EPS, which can be responsible for gel formation, particle aggregation, and bio-flocculation, was mainly regulated by their relative protein to polysaccharide contents [68].

Fig. 1. A schematic illustration of how the application of EPS can improve soil restoration efforts.
The application of calcium alginate has been shown to promote soil aggregation [69]. However, it is important to note that the binding ability of EPS-polysaccharide depends on its linear structure, length, and flexibility, which enable the formation of hydrogen bonds, Van der Waals interaction, and ionic interactions. Soil physical and chemical properties, such as pH, can influence the charges of molecules [10]. Thus, the effectiveness of pure polysaccharides in enhancing soil aggregation could vary depending on soil type.

### 3.1.2 Soil erosion control

Degraded dryland soils are typically characterized by poor aggregation and high susceptibility to erosion due to their fine-grained particles, low organic matter content, and sporadic vegetation cover [70]. Desertification exacerbates the issue by reducing the plant cover and biocrust, resulting in the expansion of barren soils. Dust emissions from these barren soils pose threats to human livelihood and the environment. Desert dust can transport highly resilient alien particle-bound microorganisms to intra and intercontinental distances, potentially becoming invaders in sensitive or pristine sink environments and posing risks as potential pathogens for food crops or humans [71].

EPS-producing bacterial strains or purified EPS in these eroded lands can be utilized to stabilize the surface, which can aid in maintaining soil architecture [72]. Positive outcomes have been observed when using EPS-synthesizing microbes like *Rhizobium tropici* and *Leuconostoc mesenteroides* to combat soil erosion. The authors concluded that the EPS produced by these strains improved the cohesion between the soil particles, enhancing soil resistance against surface erosion [73]. Microbial EPS increases the critical shear stress and surface erosion resistance, attributed to the enhanced cohesion facilitated by grain-coating biopolymer slimes [74].

A commonly employed approach for restoring eroded dryland areas involves the use of EPS-producing cyanobacteria to stimulate biocrust formation. Cyanobacterial EPS is believed to play a crucial role in stabilizing dryland soil surfaces, thereby preventing nutrient loss and dust generation [70]. In a study conducted in Hobq Desert in China, a mixed culture of EPS-producing microbes, namely *Microcoleus vaginatus* and *Scytonema javanicum*, was inoculated into sandy soils in to initiate biocrust development. Examination of the developed biocrust, conducted after three to eight years, revealed that the EPSs within the biocrust played a significant role in capturing and retaining moisture in sandy soils while protecting the soil from erosion [75]. Furthermore, the EPS-producing strain identified as *Paenibacillus mucilaginosus* VKPM B-7519 was shown to speed up biocrust recovery in the field [76].

In addition to directly applying EPS-producing strains, researchers are exploring various avenues to harness the benefits of exopolymers and their chemically modified forms as sustainable dust suppressants and erosion control [77]–[79]. For example, xanthan gum, starch, and carboxymethylcellulose were shown to be effective dust suppressants at low concentrations [80]. Sodium alginate and its chemically modified derivative significantly increased soil resistance against strength reduction and prevented dust emission [79], [81]. Large-scale field trials have demonstrated that these polymers can effectively reduce dust emissions up to 8 days post-application. However, their effectiveness is reduced after rainfall due to rapid degradation [82], indicating the need to carefully modify polymers to enhance efficiency. Moreover, the wind tunnel test indicated that biopolymers, including sodium alginate and pectin at 1% reduced wind erosion [83]. The agglomeration properties and surface adhesion of EPS contribute to forming effective surface shield in soil [63]. Thus, EPS can serve as an environmentally friendly alternative to develop as an eco-cover, either replacing or working in conjunction with conventional materials approaches such as vegetative cover and geo-membrane, to mitigate soil erosion [73] and dust emission [84].

### 3.1.3 Soil cementing agent

The EPS were also tested for their effectiveness in soil stabilization against mechanical disruption. Sand cementation was implicated to be partially biogenic because microbes isolated from cemented sand tailings produced EPS that increased strength of the sand [85]. Furthermore, inoculation of EPS-producing bacteria and cyanobacteria was shown to reduce rill erodibility, suggesting that endemic microbial inoculation is an effective bioengineering technique for managing rill erosion-prone regions [86]. As reviewed by Costa et al. [10] polymer produced by *Aureobasidium pullulans* could enhance the compressive strength of soil by more than 200%. Notably, xanthan and gellan, when used at a concentration of 0.5%, outperformed traditional cement in increasing the compressive strength of soil [10]. In another research, xanthan improved soil mechanical properties for geotechnical engineering purposes [56].

In addition to directly increasing soil strength, EPS has been found to play a significant role in enhancing the carbonate precipitation process by effectively trapping metal ions such as Ca$^{2+}$ and Mg$^{2+}$. The process, known as microbially induced carbonate precipitation (MICP), occurs when microbes facilitate carbonate formation due to supersaturation associated with certain biochemical
activities. MICP is applicable in various fields, serving as a sealant in underground geology, and countermeasures for preventing soil erosion. Additionally, this biocalcification is a type of carbon sequestration [87], highlighting the potential of microbial polymers as an economically competitive and environmentally friendly alternative material for use as a soil binder or cementing agent.

3.1.4 Biohydrogel to improve soil water holding capacity

It is widely accepted that microorganisms produce EPS as a defense mechanism against environmental stress. For instance, under desiccation conditions, *Pseudomonas* sp. increased its production of EPS-polysaccharide [88]. Similarly, *Pseudomonas putida* responds to water-limiting conditions by boosting alginate production, protecting the resident cells from desiccation stress and enhancing their chances of survival [89]. EPS are hygroscopic in nature, allowing it to retain substantial amounts of water in the microenvironment, even when surrounding bulk soil lacks moisture [72].

It has been suggested that the production of EPS can create hydraulic decoupling within the microenvironment by reducing hydraulic conductivity and increased water retention. This can maintain the microenvironment hydrated, protecting cells during drainage, or potentially reducing osmotic stress for soil microbes when rapid soil rewetting occurs during rainfall [90]. A recent microcosm study provided evidence for the effects of EPS-producing strain *B. subtilis* NCIB 3610 on cumulative and local water loss and hydraulic decoupling in soil. The authors concluded that this EPS-producing strain drastically alters the architecture of the soil pore space, which in turn affects the rates and spatial distribution of soil water losses [91]. EPS also play a role in reducing evaporation from soil. In soil treated with EPS, water loss occurs slower than control soil without EPS [92]. Moreover, EPS produced by *Sinorhizobium meliloti* were found to have concentration-dependent effects on the rate, extent, and variability of pore water evaporation in micropore-sized chambers [93].

Biohydrogels absorb water owing to their hydrophilic functional groups, while their resistance to dissolution is attributed to the cross-links between network chains [94]. It is important to note that specific components of EPS can have different effects on their water retention capabilities. For instance, polysaccharides can significantly increase the water-holding capacity of pure sand, whereas protein has minimal impact on the hydrodynamic properties of fine sandy soil [95]. Purified polysaccharides can retain 50-70 g of water per gram. Nevertheless, it is crucial to understand that the water-holding capacity of polysaccharides depends on their structural characteristics [92]. Among the polysaccharides studied for their bio-hydrogel properties, xanthan stands out as one of the most extensively researched. Even at concentrations of less than 1%, xanthan can enhance both water-holding capacity and porosity of sandy soils [96]. These microbial polymers, such as xanthan, offer a promising alternative to synthetic hydrogels for improving soil water-holding capacity [56]. However, it is important to conduct careful concentration testing to avoid potential issues like soil cementation. Also, EPS can exert an influence on soil water repellency, which, in turn, affects both infiltration and soil water retention [97].

3.2 Role of microbial EPS in enhancing soil biological properties

3.2.1 Soil microbial diversity and enzyme activity

Soil exhibits inherent heterogeneity and diversity. Its spatial arrangement generates a multitude of micro-habitats, concurrently accommodating microorganisms that occupy distinct niches. Thus, soil microbial communities exist in the form of individual microaggregates, resembling biogeographical islets, i.e., microorganisms in one microaggregate remain isolated from those in other microaggregates [98]. Thus, it is intuitive to assume that soil EPS content could influence soil microbial community diversity. Indeed, the composition of microbial communities is closely associated with soil EPS content in semiarid grassland [99]. Furthermore, introducing glucose into the soil to stimulate biofilm development has been shown to enhance Shannon diversity [62].

While it is acknowledged that improved soil aggregation is correlated with greater diversity in soil microbial communities, only a few studies reported changes in microbial diversity during the application microbial EPS for bioremediation or soil restoration purposes. Some studies have shown that the inoculation of EPS-producing strains can positively affect soil microbial diversity. For example, EPS-producing strain identified as *Paenibacillus mucilaginosus* VKPM B-7519 was found to speed up biocrust recovery in the field. This strain stimulated the assembly of heterotrophic communities in the topsoil before the commencement of autotrophic cyanobacteria, and it significantly increased the abundance of bacteria and actinomycetes [76]. *Pseudoalteromonas agarivorans* Hao 2018 increased the abundance of beneficial microorganisms [100]. In addition, the inoculation of two indigenous heterocystous cyanobacteria, *Nostoc ellipsosporum* HH-205 and *Nostoc punctiforme* HH-206, increased microbial activity in salt-affected areas [66]. These findings collectively suggest
that the application of microbial EPS can enhance soil microbial diversity by improving soil aggregation.

During the application EPS or EPS-producing strains to soil, auxiliary tests were conducted to assess soil enzyme activities. The EPS-producing strains *Pseudoalteromonas agarivorans* Hao 2018, *Pseudomonas chlororaphis* A20 and *Bacillus proteolyticus* A27 were found to enhance enzyme activities in soil [100], [63]. Similarly, EPS of cyanobacteria *Tolyphorix tenuis* and *Microchaete tenera* increased β-glucosidase, urease, protease, phosphomonooesterase, aroylsulphatase, and dehydrogenase activity in silty clay loam soil [101]. Furthermore, when inoculating the EPS-producing cyanobacterium *Microcoleus vaginatus* ATHK43 to promote biocrust development, invertase and dehydrogenase activities were observed to significantly increase after 90 days of inoculation [102].

### 3.2.2 Plant growth promotion and stress alleviation

Microbial EPS can alleviate abiotic stresses in plants, such as salinity, drought, and temperature fluctuations. These protective mechanisms stem from the ability of EPS to bind to metals and ions, enhance soil aggregate stability, and improve water retention. EPS effectively mitigates plant stress through several mechanisms [72]. One of these mechanisms involves EPS indirectly reducing the uptake Na+ by plants by absorbing excess Na+ ions in the soil. Another mechanism is forming a protective barrier around plant tissue by EPS, providing insulation against temperature fluctuations [103]. This barrier also enhances plant-microbe interaction and surface attachment [104]. Lastly, EPS’s ability to promote plant growth is associated with improved soil structure and biological activities [72].

Several bacterial strains, including *Pantoea*, *Bacillus*, *Actinomycetes*, *Rhizobium*, *Arthrobacter*, *Bradyrhizobium*, and *Pseudomonas*, have been found to produce EPS under stress conditions, which serves as protective effect for plants facing drought and salt stress. For instance, *Pseudomonas putida* GAP-P45 alleviated PEG induced drought stress in sunflower seedlings, likely by forming biofilm on the root and improving soil structure [105]. EPS-producing strains of *Pseudomonas* and *Bacillus* have demonstrated their ability to protect *Arabidopsis thaliana* from osmotic stress induced by 25% PEG [106]. Treatment of wheat and chickpea with EPS-producing strain *Agrobacterium pusense* has shown positive effects on the physiological parameters of these plants when subjected to intermittent soil drying [107]. EPS producing strain *Pseudomonas entomophila* PE3 enhanced growth, yield, and tolerance of sunflower under salt stress [108].

Another benefit of microbial EPS is related to the fact that EPS can stabilize heavy metals in soil, thus limiting their plant uptake. For instance, the EPS-producing strain *Pseudoalteromonas agarivorans* Hao 2018 alleviated lead (Pb) stress in packchoi plants grown in soil that has been experimentally polluted. This was evidenced by an increase in plant biomass and a reduction in the Pb content in edible tissue [100]. Similarly, EPS extracted from *Bacillus* sp. S3 proved effective in mitigating cadmium (Cd) stress in *Oryza sativa* L. It not only increased the plant biomass but also lowered Cd accumulation and transport and minimized oxidative stress. EPS application enhanced Cd retention in the shoot cell walls and root vacuoles and altered the expression of genes involved in cell wall formation and antioxidant defense systems [109]. Thus, the utilization of EPS-producing strains emerges as a promising solution to address biotic and abiotic stresses in plants, thus preventing crop loss in the face of climate change and global water shortage.

### 3.3 Role of microbial EPS in enhancing soil chemical properties

Microbial EPS can influence soil chemical properties in several ways. EPS influences the stability of soil organic matter, primarily through its effect on soil aggregation [110]. Enhancing soil aggregation and its stability could minimize SOM decomposition. A recent study utilizing scanning transmission x-ray microscopy coupled with near edge x-ray absorption fine structure spectroscopy has revealed that intact microaggregates are capable preserving simple organic carbon [110]. Furthermore, 13C-labeling experiments coupled with LC/MS analysis have revealed that biocrust retain higher abundance of various metabolites, especially amino acids and organic acids, compared to subcrust [111]. These findings suggest that microbial EPS might influence the composition of SOM.

 Soil microbial EPS influences nutrient accumulation in soil by affecting soil aggregation [63]. EPS may prevent nutrient losses during periods of heavy rainfall by retaining the metabolites and nutrients [70]. Some bacterial species, such as *B. subtilis* increase their EPS production in nutrient-deficient conditions [72]. *Paenibacillus mucilaginosus* VKPM B-7519 has been found to increase nutrient contents in soil [76]. Furthermore, EPS is utilized as carbon source by soil microbial communities. Costa et al. demonstrated that EPS of *Acidobacteria* is metabolized by several bacterial and fungal taxa [112].

Microbial EPS can significantly impact the composition and stability of biomolecular carbon, nitrogen (N), and phosphorus (P) in soils by influencing the mineral-organic associations. EPS was shown to be
absorbed and co-precipitated with dissolved and colloidal aluminum species in soil [113]. Moreover, associations of EPS with soil organic and inorganic components not only affect the composition of both immobile and mobile organic matter but also the reactivity of minerals [10]. Biocrust development by inoculating EPS-producing cyanobacterium Microcoleus vaginatus ATHK43 has been found to increase soil electrical conductivity, total N, potassium, calcium, magnesium, cation exchange capacity, and chlorophyll content in surface soil [102].

EPS also helps regulate the diffusion of organic carbon and other nutrients, thereby regulating elemental bioavailability in the soil. For example, Paenibacillus mucilaginosus VKPM B-7519 was shown to increase content of total P, available N, and available P in developing biocrust [76]. Another EPS-producing strain, Pseudoalteromonas agarivorans Hao 2018, reduced the available Pb content in soil by up to 38.1%, and increased soil pH, and soil nutrient content [100]. Zhang et al. reported that the interaction of EPS with ubiquitous soil ferrihydrite may affect the mobility and fate of various hydrocarbons [114]. Moreover, the EPS produced by a strain of Enterobacter was observed to increase P-solubilization when added to the culture medium. This effect is likely due to the EPS absorbing solubilized P and allowing the additional release of soluble P from insoluble P [115].

Last but not least, EPS components can function as electron shuttles in the corrosion process. EPS can interact with iron ions to cause anodic dissolution and promote corrosion. EPS also can play a role in increasing electronic potential and reducing electronic resistance, thereby enhance the corrosion current by facilitating electron transfer and metal dissolution [116]. The rock-inhabiting fungus Knufia petricola produces a corrosive EPS-poly saccharide [117].

4. Stabilization and degradation of soil pollutants facilitated by microbial exopolymers

Soil in many industrialized countries is becoming increasingly contaminated with xenobiotics, which pose significant risks to public health and the environment. These pollutants originated from various sources, including, but not limited to industrial and municipal wastewaters, leachates from landfills, leaking underground storage tanks, and urban runoff. Microbial EPS facilitates the stabilization and biodegradation of pollutants in soil by several different mechanisms, depending on the nature of the pollutant. Fig. 2 shows how microbial EPS offer several advantages due to their biodegradability, lower toxicity, and adaptability to different environmental conditions [118].

4.1 Stabilization of heavy metals by microbial exopolymers

Numerous in vitro studies have explored the ability of microbial EPS to absorb or immobilize various heavy metals [118]. Several EPS-producing bacteria, including Azotobacter, Paenibacillus, Klebsiella, Bacillus, and Pseudomonas, have been found to adsorb heavy metals [72]. For instance, EPS produced by Azotobacter was effective in immobilizing heavy metals, Cd and Cr, and reducing their uptake by wheat [119]. In another case, the EPS-producing strain Pseudoalteromonas agarivorans Hao 2018, stabilized Pb in contaminated soil [100]. The bioremediation of Pb by Pseudomonas sp. W6 was attributed to the biosorption capacity of the exopolysaccharide produced by the strain [120]. Furthermore, research has shown that EPS from a fungus Aspergillus tubingensis F12 could leach various heavy metals from soil in a column leaching experiment, with minimal effect on soil microbial community [121]. In addition to heavy metal stabilization, some microorganisms produce EPS that can be used to stabilize radionuclide. For instance, a thoriotolerant bacteria, Providencia thoriotolerans AM3, produces EPS that effectively binds radionuclide thorium (Th) [122].

Due to its diverse composition, EPS contains ionizable groups such as amino, carboxyl, hydroxyl, phosphate, and sulfate. As a result, microbial EPS can bind to positively charged heavy metals via electrostatic interactions [72] [84]. The absorption behavior of a particular microbial EPS can be influenced by its surrounding environment, particularly soil conditions. Factors like soil pH, which impact the charges of molecules, play a pivotal role in this regard [123]. For
instance, under acidic to slightly alkaline pH conditions, galacturonic, glucuronic, and alginic acids are responsible for soil Cr(VI) stabilization [124]. Additionally, sorption behavior of different bacterial EPS can be influenced by types of mineral surfaces [125], probably due to their structural difference. The ability of EPS-polysaccharide to bind heavy metals depends on its linear structure, length, and flexibility, which collectively enable the formation of different interactions [123]. Apart from soil factors influencing the EPS function, some microbial strain changes the properties of their EPS in different environments. For instance, heavy metal tolerant strain Bacillus sp. S3 can produce EPS with altered properties in response to exposure to various heavy metals [126].

In addition to binding heavy metals, EPS also adsorbs organic pollutants such as phenanthrene, benzene, and dye molecules, which might be related to their hydrophobic regions [84]. These findings illustrate the significant potential of microbial EPS in mitigating soil contamination by a wide range of pollutants, including heavy metals, radionuclides, and various xenobiotics. As a result, the application of EPS can help reduce the transport of solids in runoff water and avert contamination of both surface and groundwater [84], [73].

4.2 Enhanced degradation of hydrocarbons by microbial EPS

Petroleum products are one of the major pollutants found in soil. One of the compound groups that ranks among the highest priorities on the list of harmful and/or toxic contaminants by US Environmental Protection Agency is polycyclic aromatic hydrocarbons (PAHs). These xenobiotics exhibit both acute and chronic toxicity, and they can have the potential to be carcinogenic, mutagenic, or teratogenic. Due to their distinctive chemical structures, hydrocarbons are known to be resistant to biodegradation in the natural environment, leading to their accumulation in the food chain. While various microorganisms have demonstrated the capability to metabolize hydrocarbons, their effectiveness is limited due to their low abundance in nature. Also, the survival of these microorganisms in the natural environment is uncertain due to various environmental factors [6]. The addition of emulsifiers can be employed to enhance the bioremediation of pollutants with poor water solubility [84].

Several microbial strains, such as Streptomyces griseorubens GD5 [127] and Nostoc flagelliforme [128], can produce EPS with emulsifying activity. In another example, a moderate halophilic bacterium Halomonas eurihalina has been found to produce an exopolysaccharide with the capability to emulsify a wide range of hydrocarbons including n-tetradecane, n-hexadecane, n-octane, mineral oils, petrol, and crude oil [129]. EPS from Zoogloea sp. and Aspergillus niger were able to accelerate pyrene degradation in contaminated soil. Notably, when these two EPS types were combined, the degradation was further enhanced [130]. Furthermore, research has shown that EPS from Ochrobacterium anthropic strain AD2, possessing bioemulsifying activity, can significantly improve the degradation of diesel and fuel oil mixtures in both microcosm and biopile experiments [131].

EPS promotes degradation of hydrocarbons by solubilizing these substrates due to their amphiphilic property [132]. This enables the hydrocarbons to diffuse through the aqueous phase to the cell surface. In support of this, confocal laser scanning microscopy revealed that a GFP-labeled strain of Pseudomonas putida was found to grow directly on phenanthrene, forming a biofilm on accessible crystalline surfaces. The biofilm formation appears to be vital in overcoming mass transfer limitations and achieving improved PAH degradation [6]. In another study, phenanthrene-degrading bacteria capable of producing EPS, Spingobium sp. PHE3 and Micrococcus sp. PHE9, were shown to enhance mass transfer of phenanthrene from silicone oil to water, and that biodegradation mainly occurred at the interfaces. This is likely attributed to the increased solubility of phenanthrene in the presence of EPS polysaccharides and proteins [133]. Additionally, it is noteworthy that in the presence of hydrocarbons, the produced bioemulsifier exhibited a higher content of uronic acid, acetyl, and sulfate groups compared to the control containing glucose [129]. GRSP was shown to interact with phenanthrene in a size-dependent manner, where a fraction containing proteins larger than 10 kD molecular weight exhibited stronger interactions. GRSP interacted with phenanthrene mostly through hydrophobic, NH-π, and hydrogen bonds [38].

4.3 Environmental and microbial factors affecting exopolymer-based bioremediation

Environmental factors profoundly influence the effectiveness and outcomes of bioremediation processes because both production and molecular characteristics of microbial EPS can be influenced. Variables like, pH, temperature, moisture levels, salinity, and the chemical makeup of heavy metals wield considerable influence EPS production by microorganisms [56], [57]. Soil type influences the macromolecular distribution and monosaccharide composition of the EPS-polysaccharide in induced biocrusts [134]. Soil characteristics and the specific region within the soil, such as the topsoil, play a critical role in EPS biosynthesis and molecular characteristics through its influence bacterial populations.
and the composition of functional genes [26], [50], [53], [64], [65].

Soil microbial EPS production and structural characteristics can also be modulated by stress conditions as well as the addition of various supplements. For example, a soil microcosm experiment showed that the production and composition of EPS *Pseudomonas putida* GAP-P45 were modulated under stress conditions. Rhamnose was reported to be the major sugar under drought, osmotic, and thermal stress. Inoculation with this strain resulted in more soil aggregation and aggregate stability under different stress conditions [105]. Properties of EPS by soil microbial community were influenced by substrate type added to experimental soil. Chitin supplementation produced EPS with better water retention in soil than a soluble carbon substrate, N-acetylglucosamine [135]. Inorganic substances were also shown to modulate microbial EPS production. ZnO nanoparticles enhanced EPS production by 596.1% in liquid culture of *B. subtilis* strain JCT1. The produced EPS was shown to increase soil aggregation, moisture retention, and soil organic carbon [136]. In another research, addition of clay increased EPS production in soil more than labile substrates did (starch and cellulose) [67].

In addition to environmental factors, microbial factors also play important roles in the successful application of EPS. These factors encompass microbial community composition, bacterial metabolic capability, biofilm formation, competition, and cooperation between indigenous and exogenous bacteria [57]. Microbial competition and cooperation within microbial communities are forces that can significantly impact bioremediation. The balance between these interactions can either enhance or hinder the effectiveness of pollutant degradation [69]. Competition can occur between different species of bacteria or between bacteria and fungi, often involving the utilization of limited nutrients available. In some cases, microbial species release metabolites that inhibit the growth of others, affecting the overall bioremediation process [70]. The role of indigenous is also crucial in bioremediation. Indigenous bacteria are well adapted to the local environment [57], [69], [71], thus understanding the stability and physiological adaptations of these microorganisms is essential for successful bioremediation.

5. Current challenges and future perspectives

As detailed in previous sections, currently available studies demonstrate the positive impact of EPS-producing strains on soil physical, biological, and chemical properties, and on the immobilization and degradation of pollutants. However, there are still several challenges and unanswered questions that require further investigation. The challenges include the optimization of EPS production, the selection of appropriate microbial strains, and the development of cost-effective and safe bioremediation strategies. In addition, the long-term impact of EPS on soil health and ecosystems needs to be better understood. Future research should focus on developing more efficient and sustainable bioremediation strategies that can address these challenges.
of soil pollutants. However, several challenges must be confronted to enhance their effectiveness and facilitate the large-scale use of microbial EPS for soil restoration and remediation. These challenges can be categorized into three primary areas: the effectiveness and safety of directly inoculating EPS-producing microbes into the soil, insufficient effort on aligning the molecular characteristics of EPS with the specific application purposes, and limited information regarding the characterization of soil-extracted EPS. In the following discussion, we attempt to address the challenges and propose potential directions for future research.

5.1 Effectiveness and safety of direct inoculation of EPS-producing microorganisms

The effectiveness of direct inoculation of EPS-producing microorganisms into natural soils remains uncertain with respect to their survival and EPS production in the natural environment [10]. Recent trends in this field have concentrated on strategies to address issues related to the survival of inoculated microorganisms to improve the effectiveness of soil restoration and remediation. One such approach involves harnessing desert microorganisms for dryland soil restoration, given their inherent advantages adapted for xeric conditions. An alternative method involves applying native microorganisms isolated from the vicinity of the affected site. This approach circumvents challenges associated with competing against the native microbiota, which has undergone extensive selection by environmental conditions [71]. Another approach is the application of mixed microorganisms or heterogeneous microbial consortia [118], which could result in better effectiveness and survival compared to the inoculation of single microorganisms or homogenous microbial cultures. Additionally, immobilized microorganisms could offer better effectiveness as they have superior biological reaction kinetics and improved biosorption [118].

Another concern when introducing EPS-producing microorganisms into natural soil is the lack of a comprehensive understanding of how indigenous microbial communities respond to external perturbations, such as additive manipulations. Introducing microorganisms into natural environments poses the potential risks of altering the community structure of indigenous microorganisms [71]. To mitigate the safety concern associated with using living cells, the application of dead cell biomass, including its EPS can be considered [118]. Moreover, extraction and application of crude EPS, as well as EPS-polysaccharides and EPS-proteins, can also help mitigate the risks, although downstream processing may entail additional costs related to equipment and labor. However, these costs remain more economical compared to the production costs associated with synthetic polymers [137]. These expenses can be reduced by enhancing EPS production efficiency through various means. One approach to reducing the production cost of microbial EPS involves optimizing cultivation time and conditions as well as utilizing organic waste for cultivation to improve EPS yield [138]–[140]. Metabolic engineering is another potential strategy to enhance EPS-polysaccharide production by overexpressing one or more genes involved in biosynthesis [20]. Fig. 3 illustrates how different EPS-based techniques can vary depending on their potential effectiveness, cost, and safety.

5.2 Structure and activity relationship of microbial EPS

It is widely accepted that the composition and molecular structure of exopolymers greatly influence their functionality. However, limited efforts are made to establish connections between the molecular features of EPS for the application in soil. Concentration is also an important factor to consider before applying EPS in the field. For example, xanthan can be used to enhance soil water holding capacity and suppress dust formation. However, it may also lead to soil compaction, which can have adverse effects on plant growth and seed germination. The use of high concentrations of xanthan gum can result in clogging of soil pores [56]. Hence, it is crucial to carefully investigate EPS’s appropriate molecular features and concentration before applying them in soil restoration and remediation efforts.

Tailoring the molecular structure of microbial EPS to align with its function can significantly enhance the effectiveness of soil restoration or remediation efforts. In addition to exploring the microbial EPS that meets the purpose of a specific application, it is possible to modify the structure of EPS constituents, particularly polysaccharides, to improve their function and reduce the required amount of EPS for a given application [137]. Modifications such as acetylation, methylation, and phosphorylation of functional groups within EPS, can modify their interaction with various molecules [118], thereby influencing their suitability for soil restoration and bioremediation purposes. Chemical methods can be used to modify structures of polysaccharides. Moreover, genetic engineering has been shown to be a valuable approach in this regard, with successful instances where researchers used genetic engineering approaches to modify or enhance the properties of exopolysaccharides. For instance, xanthan was modified to exhibit different acetylation, pyruvylation, and side chain differences. In another case, acetan from Acetobacter xylinum was
modified through mutagenesis for higher viscosity [141].

5.3 Limitation on the characterizing EPS of soil microbial community

While analytical methods for determining the structure and composition of polysaccharides extracted from microbial strains are well established, the compositional and structural analysis of EPS within soil microbial communities remains largely unexplored due to its complexity. It is essential to develop feasible approaches for characterizing EPS of soil microbial communities (i.e. soil extracted EPS) better understand its distinguishing characteristics in healthy versus degraded soils. Furthermore, this will allow for evaluating how exogenous EPS interacts with soil components during EPS-based soil restoration and remediation efforts.

Currently available studies predominantly focus on quantifying major EPS components, particularly EPS-polysaccharides and EPS-protein. Conventional methods such as NMR and mass spectrometry for polysaccharide or protein analysis will require extensive cleaning and separation steps to draw meaningful conclusions. Thus, researchers seek more feasible approaches to assess the overall compositional diversity of EPS extracted from various soils. Recent studies have employed three-dimensional fluorescence spectra to compare the overall composition of EPS extracted from suspended sludge and biofilm [142], as well as water-extractable organic matter in soil [143] and GRSP [35]. This approach can be used to compare compositional features of EPS extracted from different soils and to observe changes during soil restoration and remediation.

Culture-independent approaches can be valuable for exploring the diversity of EPS-producing communities in different soil. In a recent metagenomics study, it was found that Betaproteobacteria were the major group containing the genes involved in the biosynthesis of exopolysaccharides and lipopolysaccharides in the bulk soil, whereas in biocrust, the major potential producers of adhesive polysaccharides were Alphaproteobacteria, which could be either Cyanobacteria or Chloroflexi, along with Acidobacteria [144]. Moreover, metagenomics can assist in identifying the responsible genes and pathways for novel or significant exopolymers.

6. Conclusion

In conclusion, land degradation is not only affected by climate change but also contributes to it by releasing increased greenhouse gases. Given that soil contains the largest terrestrial carbon stock [145], it is imperative that we work towards maintaining soil carbon stability. We believe that microbial EPS can play a crucial role in protecting soil organic carbon in managed and restored lands and help bolster soil carbon sequestration efforts. Concurrently, microbial EPS can serve as a valuable tool in stabilizing pollutants in soil, thereby minimizing their leakage into groundwater and uptake by crops. Thus, microbial EPS-based technologies hold great potential as an eco-friendly, highly sustainable, and cost-effective method for soil restoration and bioremediation.

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Soil Bioremediation


Бичил биетний экзополимерийг хорсний нохон сэргээлтэд ашиглах нь: оноогийн төлөв байдал, ирээдүү нийг хандлага

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1. Оршил

1.1. Хорсны доройтол болон бохирдлын ойлгоог


Хүнс, Хөдөө Аж Ахуйн Байгууллага хорсны доройтол болон бохирдлын ойлгоог зөвлөгчийн материал 

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1.3 Энэхүү тоймын зорилго

Бичил биетий экзополимерийг хүн, аангаах ухасан, конголийн үндэс, гоосанай гэх мэт толгой ёслолын хэрэг зүйлд ашиглалт салаар нэлээд зорьдог бичилдээ, вэбсайт, асар чухал хүн ахлагчдын сүлээгэд үйл ажиллагаа нэлээд болон амлин энэхүү нэгж болон зорьдог бичилдээ бичил биетний экзополимерийг нийлэж байна. Энэ хэсгээс амьдралт зочилогчид болон амьдралт зочилогчдын зүйл нэлээд бичигдэсэн байдаг. Бичил биетий экзополимерийг аммиакийн волар нэлээд зорьдог бичилдээ нь мөөгөнцөр ёсны төрөл байнаг нэгж болон зорьдог бичилдээ бичил биетний экзополимерийг аммиакийн волар нэлээд зорьдог бичилдээ нь мөөгөнцөр ёсны төрөл байнаг нэгж болон зорьдог бичилдээ бичил биетний экзополимерийг нийлэж байна. Энэ хэсгээс амьдралт зочилогчид болон амьдралт зочилогчдын зүйл нэлээд бичигдэсэн байдаг. Бичил биетий экзополимерийг хүн, аангаах ухасан, конголийн үндэс, гоосанай гэх мэт толгой ёслолын хэрэг зүйлд ашиглалт салаар нэлээд зорьдог бичилдээ, вэбсайт, асар чухал хүн ахлагчдын сүлээгэд үйл ажиллагаа нэлээд болон амлин энэхүү нэгж болон зорьдог бичилдээ бичил биетий экзополимерийг нийлэж байна.
хөрсний эрүүл төлөв байдлын зүйл нөлөө үзүүлж байгааг харуулах нэлээд олон судалгаа хэвлэгдсэн байна. Энэхүү тойм тэмдэглэл бол бичил биетний экзополимер нь хөрсний физик, хими, биологийн шинж чанарт хэрэглэж байгааг харуулан дагуулах нэлээд олон судалгаа хэвлэгдсэн байна. Энэхүү тойм өгүүлэлд бид бичил биетний экзополимер нь хөрсний физик, хими, биологийн шинж чанарт нөлөөлөх замаар хөрсний хөрсний эрүүл төлөв байдлыг сайжруулах механизмыг тусгахыг зорилоо. Бид эхлээд бичил биетний экзополимерийн бүрэлдэхүүн, бионийлж болон уургийн талаар төвлөж дурдана. Дараа нь бичил биетний экзополимер болон тэднийг бичил биетний долоо хүртэл нийгдэн судалгааны ополтуудыг тоймлон харуулна. Тогтgonsон нь бичил биетний экзополимерийг хөрсний нохон сурагчдын шинж чанар нөлөөлөх замаар хөрсний эрүүлтөл бол бичил биетний экзополимерийн бүрэлдэхүүн, бионийлж болон уургийн талаар төвлөж дурдад хөрсний бичил биетний экзополимер нь хөрсний физик, хими, биологийн шинж чанарт нөлөөлөх замаар хөрсний эрүүл төлөв байдлыг сайжруулдаг механизмыг тусгахыг зорилоо. Бид эхлээд бичил биетний экзополимерийн бүрэлдэхүүн, бионийлж болон уургийн талаар төвлөж дурдад хөрсний бичил биетний экзополимер нь хөрсний физик, хими, биологийн шинж чанарт нөлөөлөх замаар хөрсний эрүүл төлөв байдлыг сайжруулдаг механизмыг тусгахыг зорилоо. Бид эхлээд бичил биетний экзополимерийн бүрэлдэхүүн, бионийлж болон уургийн талаар төвлөж дурдад хөрсний бичил биетний экзополимер нь хөрсний физик, хими, биологийн шинж чанарт нөлөөлөх замаар хөрсний эрүүл төлөв байдлыг сайжруулдаг механизмыг тусгахыг зорилоо.
3. Biocatalytic exopolymers for environmental remediation

3.1 Biocatalytic exopolymers for environmental remediation

3.1.1 Biological activity of the biocatalytic exopolymers

The self-assembled organization of exopolymers in the environment has been observed since the 1990s [57, 58], but recently, researchers have focused on the role of exopolymers in the environmental impact of organic and industrial effluents. Exopolymers are capable of forming stable aggregates in the environment, which can protect the soil from physical, chemical, and biological degradation [42], [60]–[62]. Microcosms composed of natural plants and microorganisms have been used to study the role of exopolymers in environmental remediation [42], [60]–[62]. The self-assembled structure of the biocatalytic exopolymers can protect the environment from pollution and enhance the efficiency of the biocatalytic process. Therefore, the use of biocatalytic exopolymers in environmental remediation is a promising approach.
Pseudomonas chlororaphis A20 болон Bacillus proteolyticus A27 элс, лаг шаварлал хорсний усанд төсөөртөгээ макроагрегатын изэгцүүлэл болохыг тогтоож [63]. Энэ нэг судалгаа гарагын төсөөртөгээ B. amiloliquefaciens р16 нь бактериийн хүчин төсөөрүүг садны өндөрт хангаж, хорсийн аргагийг дэлжээ багаан тогтооноо [64] болохыг хорсийн түрлэлд дүрдэгдүүлж байна. Элсэн манхханд урдага ургамлын бактери болок Microbacterium arborescens-ийн нийлэгч хэрэгтэй экзополимер элсэрлээг хорсийн аргагийг изэгцүүлэх садны өндөрүү болохыг тодорхойлсон [65]. Индемик цаанобактериуд болох Nostoc ellipsosporum НН-205 болон Nostoc punctiforme НН-206-ийг давсжилт ихээлт энэхдүгээр суулгаан дүрсгэлтийн түр улмаас хорсийн аргагийг тогтоосны үүр нөлөө нь хөрсний төрлөөс хамаарч, хөрсний агрегацийг дэлжээ чадвартай багаан болохынхаа хуранд байна [71].

Экзополимер нийлэгч хэрэгтэй бактерийн омог эсвэл цэвэр зүрх гарсан экзополимерийг элсэрлээд арс нь газруудад гадаргууг нь тогтоорхуулахдаа ашиглаан эхлээд бөгөөд буурахаар хорсийн бүтцийг хадгалахад түлхэх болдог [72]. Rhizobium tropici, Leuconostoc mesenteroides эзээр экзополимер нийлэгч хэрэгтэй бичил биетнуудийг хорсийн элсэрлээгээ эмхээдхэн ашилаход зэрэг ѷр дун ажигласан ба тэдгээрийн экзополимер хорсийн элсэрлэээг хөрсний тогтвортой байдлынд нээлтээр нь сэргийлээ. Түрүү, хорсийн элсэрлээч хөрсний аргагийг дэлжээ чадвартай багаан болохынхаа хуранд байна [73], [74]. Элсэнд хүрээгээр газар нутгийн тээвэрлээд биоуд биологоо газрын тээвэрлээд биохимийн орлогд нийлэгч хэрэгтэй цаанобактерийг түрэмгэлт хэрэгжилтэй. Цаанобактерийн экзополимер хорсийн химийн тээвэрлээд бүтцийн төлөвөөд аргаар өөрчилсөн уламжлал хорсний тогтвортой байдлыг нэмэгдүүлж, тоос ялгарахаас сэргийлсэн [78]. Хорсийн химийн түгээмэл, хөрсний бүтцийн бүтцийн өөрчлөлдөө түүний усанд дүрсгэлтийн түрээр нь хөрсний элсэрлээг ашиглахад эерэг үүрд нэмэгдээд болохыг тогтоож [75]. Панацителийн экзополимер Paenibacillus mucilaginosus VKPM В-7519 омгийг талбайд тургын биокрастын нөхөн зэрэглээ хэрэглэж байгааг тодорхойлсон [76].

Судалгааны тодорхойлолтын дүрсгэлтийн дагуу нийлэгч бактерийн омог нийлэгч экзополимерийг болохыг тогтоож эсвэл цэвэр зүрх гарсан экзополимерийг элсэрлээд арс нь газруудад гадаргууг нь тогтоорхуулахдаа ашиглаан эхлээд бөгөөд буурахаар хорсийн бүтцийг хадгалахад түлхэх болдог [72].

3.1.2 Хорсийн элсэрлэлтийн ханаах

Хуурай газрын доройтон хөрс хийчээлн парийн ширээн, органик жиддүүд агуулж хагацаат, ургамлын бууж, сүрээг тул элсэрлэлти мөрөөгөөрөө мондог [70]. Цолжилтын улмаас судалгааны түр нөхөртөгээ багаан болохыг хорсийн түрлэлд дүрдэгдүүлж, биокраст багасагаа, хүрж шиггүй хорсийн тээвэрлэл хөрсний аргагийг дэлжээ багаан тогтооноо [64]. Энэхдүгээр суулгаан дүрсгэлтийн түр улмаас хорсийн аргагийг дэлжээч хөрсний тогтвортой байдлыг нэмэгдүүлж, тоос ялгарахаас сэргийлсэн [78]. Хорсийн газрын тээвэрлээд биологоо газрын биологоо газрын биоагрегатын толгойд орсон биологоо газрын бүтцийн төлөвөөд аргаар өөрчилсөн уламжлал хорсний тогтвортой байдлыг нэмэгдүүлж, тоос ялгарахаас сэргийлсэн [78].

Цаанобактерийн экзополимер нийлэгч хэрэгтэй бактерийн омог эсвэл цэвэр зүрх гарсан экзополимерийг элсэрлээд арс нь газруудад гадаргууг нь тогтоорхуулахдаа ашиглаан эхлээд бөгөөд буурахаар хорсийн бүтцийг хадгалахад түлхэх болдог [72].
3.1.3 Soil Bioremediation

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soil bioremediation mechanics and technologies have gained significant interest in recent years due to their potential to address environmental challenges, particularly in areas affected by heavy metals, organic pollutants, and other contaminants. The use of soil microorganisms, such as bacteria, fungi, and actinomycetes, has been extensively studied for their ability to degrade pollutants, remediate contaminated sites, and promote ecological balance. This chapter reviews the current state of soil bioremediation technology and highlights emerging trends and challenges in the field.

3.1.4 Biohydrogel Functionalization with Biopolymers

The use of biopolymers in biohydrogels is gaining increasing attention due to their unique properties, such as biodegradability, biocompatibility, and potential for tunable gelation. These properties make them suitable for various applications, including drug delivery systems, regenerative medicine, and environmental remediation. This section discusses the functionalization of biohydrogels with different biopolymers, including polysaccharides, proteins, and synthetic polymers, to improve their performance and adaptability.

Bacterial biohydrogels have emerged as a promising alternative to traditional hydrogels due to their excellent mechanical properties and tunable characteristics. The chapter reviews the current research on the synthesis, characterization, and applications of bacterial biohydrogels, emphasizing their potential in controlled drug delivery, tissue engineering, and other biomedical applications.
3.2 Хорсний биологийн шинж чанар

3.2.1 Хорсний бичил биетний олон янз байдал, энэ нь хийсэн судалгаанууд хэд хэд хийгджээ. Экзополимер биетний олон янын байдлыг нэмэгдүүлэх боломжтой гэлээ. Түрүүлгүүлэх болон актиномицетийн тоо хэмжээ гетеротроф бичил биетний бүлгэмдэлд нөлөөлж, \textit{Paenibacillus mucilaginosus} омог суулгаснаар хорсний бичил биетний олон янын нөлөөлж буйг цөөн хэдэн судалгаанд тэмдэглэжээ. Хөрсий бичил биетний бүгдийг нөлөөлж буйг хөрсөнд глюкоз нэмэхэд Шанноны олон янын байдалын индексийг нэмэгдүүлдэг болохыг харуулах [62].

3.2.2 Ургамлын өсөлт дэмжих, стресс бууруулах

помощь, экзополимеры Pseudoalteromonas agarivorans НАО 2018 годы.

3.3 Хорсиний химийн шинж чанарын сайжруулахад бичиг биетний экзополимерийн Thư

         Бичил биетний экзополимер хорсиний химийн шинж чанарт хэд хэд хэлээр аргаар нөлөөлдөг. Экзополимер хорсиний аргагац идэвхэд нөлөөлдөг замаар хорсин органик бодисын тогтвортой байдлын зорилго нөлөөлдөг [110]. Хорсин аргагацаа, түүний тогтвортой байдлыг идэвхэд нөлөөлдөг эрдэс ба органик хүчил, органик нүүрстөрөгчийн эхдээг нэрлэдэг [111]. Экзополимер органик нүүрстөрөгч болон бусад бактерийн экзополимер хэд хэдэн төрлийн бактери, зогсоогүй байдалд нөлөө үзүүлдэг. Экзополимер хорсин дэх угсун болон колонд хоон газарны үржүүлж хамт тунадас угсээд бололхыг судалжээ [113]. Мөн хорсин орган биологийн биол-раст угсээнд төрөл бүрийн метаболит, ялангуяа амин туршилт, био-краст нь хөрсний дуусгалуулын хөрсөнд зөөвөрлөхийг нэмэгдүүлэгч омог ашигласан [114]. Түүнчлэн нүүрстөрөгч, азот, фосфор малхий идэвхийг нэмэгдүүлдэг болохыг тодорхойлжээ [112].

         Экзополимер органик нүүрстөрөгч болон нөлөөлдөг болохыг дагцан үүрэг гүйцэтгэдэг. Экзополимер органик нүүрстөрөгч болон бусад бактерийн экзополимерын нийлэгжлээ нэмэгдүүлдэг [72]. Paenibacillus mucilaginosus VKPM B-7519 хорсин дэх тэгжээлний агуулгатай нөлөөлдөг болохыг тогтоох [76]. Уүнээс гадна, экзополимер хорсиний бичиг биетний булзгэмдлэрүүн нүүрстөрөгчийн эх угсээр болгодог. Экзополимерын нийлэгжлээ Acidobacteria бактерийн экзополимер хэд хэдэн төрлүүн бактери, моонгөүргөн бодисын солироондоо ашиглахдаг болохыг тодорхойлох [76].


Epikolíptbnь nógmíshárdik, úyrag, núcúléin xáçrarg éh mét bimolékyláas búrdlo gáa archat amin, karbóksil, fosfát, sulftát éh mét jónjík bultlímd ykgmélal. Édégér bultlíy tóslamkaktb hímn metallošatél elétrostáti xárcíptb yñgylas úyslaal [72] [84]. Üntøj éploótóygoó epikolíptbněh hórsoń metallo yngéghz chárvar nь órcíy nolofloxxgér órecíyladóx bóloróktojy. Tíyééss hórsoń pýgh mét xáçrarg ýuíylohd no chukal noloytgé [123]. Táxáylbáal, xáçrarglág bolso yshurlát xórcí ygalakturoiny xáçrarg, glukuroiny xáçrarg, algííny xylául hórsoń Crb(VI) toksugurkylás chárvar sày bájsán [124]. Món yngéghz chárvar minerraliny šinyó čáhrvaras xáhamaç bóllo [125]. Hórsoń šinyó čáhr var epikolíptbněh ýdzhvéd nolofloxxhgos gádina, zarnim bichil bítétbydúdíyé níyléjguuléch bá jór epikolíptbněh šinyó čáhr var órcíy nolofloxxgér órecíyladóx. Táxáylbáal, hórsoń metallo tászvértyt Bacillus sp. S3 ómot ý真理ál xórcí nd xáméxí hímn metallo ynd troloos xáhamaç óor óor šinyó čáhrvar epikolíptbněh níyléjguuléch bájéss é [126].

Hórsoń metallotíy bolbođgóxhos gádina epikolíptbněh nь ydrióodb šéctguuídyyhé tóslamkaktb fénhántér, béníí, bádálk bódísxg mét orgúnik boxírduuglácgy nón yngéghz chárvar bájdáy [84]. Édégér sudálayóna yd ùuyglúd nь bichil bítétby epikolíptbněh áshgáld hórsoń metallo, xáçrarg izéht elementsí, orgúnik boxírduuglácgyar boxírduon hórsoń yngéghz ýrílguuléch áshgáld bóloróktojy bóloró yhúrlug bájsán. Én é nón hórsoör dámkhujy gúniy bolso gádartugyjyý yx boxírdoń ydéslíy baaa yngéghz [84], [73].
4.2 Bi- and tri-nitrophenoxymethylation

[Text content]

4.3 Bi- and tri-nitrophenoxymethylation

[Text content]
агрегацийг нэмэгдүүлэх чадвар стрессийн үед илүү сайн байсах [105]. Хөрсний бичих биетний бүлэглэлдийг экзополимерийн шинж чанар тухайн хөрснөөс нэгсэг нэмэгдүүлэх босолго болно. Тухайлбал, түршилтэн хөрсөнд хитин болон N-ацетилглюкозамин нэмэгдүүлэх нэмэгдүүлэх чадвартай орноос. ЗнO-ний нанопартикл B. subtilis JCT1 омогийн экзополимерийн нийлэлжлүүлэг 596.1% нэмэгдүүлсэн ба энэ нь хөрсний агрегаци, хөрсний ус барих чадвартай орноос. Органик биш нэгдлүүд мөн экзополимерийн нийлэлжлүүлэг орноос. Зарим бичих биетний зүйлүүд бусад бичил биетний өсөлтийг дарангуйлах бодис нийлэгжүүлдэг [70]. Тухайн бичил биетний ынокуляция хөрсний натив бичил биетнүүд тухайн нөхцөл, бүлгэмдэлдээ дасан зохицсон [57], [69], [71] тул нөхөн сэргээлтийн өмнө натив бичил биетнүүдийн бүлгэмдлийн тогтвортой байдал, физиологийг судлах нь чухал.

5.1 Экзополимер нийлэхчүүлгэч бичил биетний экзополимер нийлэсэн хэрэглээтэй холбоотой чиг хандлага

Омын хэсэгүүдэд дурдсанын арга бол бичил биетний бүлэглэн нөлөөг нийлээж, энэ нөлөөдтөөс хүчирхээгүй бичил биетний зүйлүүд бусад бичил биетний өсөлтийг дарангуйлах бодис нийлэгжүүлэг эсвэл түүний полисахарид болон уургийн бүрэлдэхүүнийг ялгаж хэрэглэх нь эсвэл эрсдэлцэд эрсийлэн нүүрсэн эсийн биомассыг экзополимерийн хамт хэрэглэж болно [118]. Мөн бичил биетний бүлэглэн нөлөөг нийлээж, энэ нөлөөдтөөс хүчирхээгүй бичил биетний зүйлүүд бусад бичил биетний өсөлтийг дарангуйлах бодис нийлэгжүүлэг эсвэл түүний полисахарид болон уургийн бүрэлдэхүүнийг ялгаж хэрэглэх нь эсвэл эрсдэлцэд эрсийлэн нүүрсэн эсийн биомассыг экзополимерийн хамт хэрэглэж болно [118]. Мөн бичил биетний өсөлтийг нийлэхчүүлгэч бичил биетний зүйлүүд бусад бичил биетний өсөлтийг дарангуйлах бодис нийлэгжүүлэг эсвэл түүний полисахарид болон уургийн бүрэлдэхүүнийг ялгаж хэрэглэх нь эсвэл эрсдэлцэд эрсийлэн нүүрсэн эсийн биомассыг экзополимерийн хамт хэрэглэж болно [118]. Мөн бичил биетний өсөлтийг нийлэхчүүлгэч бичил биетний зүйлүүд бусад бичил биетний өсөлтийг дарангуйлах бодис нийлэгжүүлэг эсвэл түүний полисахарид болон уургийн бүрэлдэхүүнийг ялгаж хэрэглэх нь эсвэл эрсдэлцэд эрсийлэн нүүрсэн эсийн биомассыг экзополимерийн хамт хэрэглэж болно [118].
5.2 Biotech extracellular polymers, functionality and applications

Exopolymers are obtained from microorganisms, usually as a by-product of the growth of these organisms. The composition and properties of exopolymers depend on the type of microorganism and the growth conditions. Exopolymers are often used in bioremediation processes because they can be used to improve the efficiency of biodegradation processes by enhancing the immobilization of pollutants on the surface of the exopolymer. This can be achieved by modifying the properties of the exopolymer, such as its hydrophobicity or hydrophilicity. The modification of exopolymers can be done by chemical or biological methods. For example, exopolymers can be modified with fatty acids or fatty alcohols to increase their hydrophobicity, or with amino acids or sugars to increase their hydrophilicity. These modifications can be achieved by genetic engineering or chemical synthesis.

5.3 Comparative study of biotechnological and natural extracellular polymers

Exopolymers produced by different microorganisms can have different properties and applications. The choice of the type of exopolymer depends on the specific requirements of the bioremediation process. For example, exopolymers produced by Acinetobacter sp. can be used for the remediation of oil spills, while exopolymers produced by Pseudomonas aeruginosa can be used for the remediation of heavy metals. In general, exopolymers can be used to enhance the efficiency of bioremediation processes by improving the immobilization of pollutants on the surface of the exopolymer.
ялган буюу хөрсний бичил бийтнэй бүлгэлдлийн экзополимерийн бүрэлдэхүүн, бүтэц, найрлагыг тодорхойлсон хөрсний эрүүл төлөвлөгөөг нэрлэх, тодорхойхон ашиглагддаг. Төрөл бүрийн шинж чанар бүхий хөрсний бичил бийтнэй бүлгэлдлийн экзополимерийн онцлог шинж чанарыг тодорхойлсон барьж, хөрсний үүргээц бичил биетний ашиглалыг яшиглах явцад чухал ач холбогдолтой.

6. Дүгнэлт

Эцэст нь дүгнэхэд, газрын доройдод нь уур амьсгалын өөрчлөлтийн нөлөөгөөр нэмэгдэж байгаагийн дээд нөлөөгөөр нэмэгдэн хийнгээ хийж, хөрсний органик нүүрстөрөгчийн тогтвортой байдлыг хадгалагдансаа айхандаа хандуулаж нь зүйтэй. Бичил бийтнэй экзополимерийг хөрсний нөхөн сэргээлэгдэд ашигланаа хүндрэлтэй гэж үгүй байна. Хөрсний зэрэгцээ, бичил бийтнэй экзополимерыг хөрсий бихир дүүрлэлэг нэгдлүүдийн эсвэл бихир дүүрлэлэг нэгдлүүдийн бүрэлдэхүүн буюу бүтэц, найрлагыг тодорхойлох хүчин тодорхойлсноор хөрсний эрүүл төлөвлөгөө нь үүрэгтэйг тодорхойлохоос гадна, экзополимерийг хөрсний нөхөн сэргээлэгдэх ашиглалыг яшиглэд чухал ач холбогдолтой.

Талархал

Энэхүү ажил нь Олон Улсын Шинжлэх Ухааны байгууллагуудын санхүүжилттэй Холбооны хамтын дагуулах болуулахад багтвэр болон тээврийн нөлөөлдөг. Бичил бийтнэй экзополимерийг хөрсний нөхөн сэргээл, ремедиацад ашиглах байгаль орчин эсвэл эрүүл хүчин өртөг багатай технологийн хөгжүүлэх боломжтой.

Ашигласан материал


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