MICROBIAL BIOPOLYMERS: A REVIEW ON BREAKTHROUGH APPROACH TO SOIL TREATMENT

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Abstract
Soil, more commonly known as dirt, is an intricate combination of compounds such as organic matter, minerals, gases, liquids, and lifeforms, all of which help to nurture life. It is universally acknowledged that environmental issues such as soil degradation (erosion and desertification) have a global impact on many agricultural lands. These issues have led to a reduction in soil quality, a low yield of crops, poverty, unemployment, and rural-urban migration. Since the beginning of civilization, the soil has been mixed with cementitious binders to prevent the above. Recently, because of the excessive use of chemicals and synthetic products, the requirement for eco-friendly and natural/green substitutes is increasing. This is because cement, which is an extensively used soil treatment substance, significantly contributes to greenhouse gas emissions. Synthetic polymers, microbial induction, and biopolymers are among the alternatives that are being explored. This article analyzes the most current applications of microbial biopolymers in soil improvement. Biopolymers are microbiologically enhanced polymers that are high- ductile, non-toxic, & environmentally friendly. Recent research and microscopic studies on interactions of soil and biopolymer and their soil-strengthening mechanisms are reviewed in this article.

Keywords: Anti-desertification; Desertification; Drought-Stress; Exopolysaccharides (EPS); Microbial Polysaccharides.

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1. INTRODUCTION

Soil, an essential and irreplaceable natural asset, holds immense significance in sustaining life on our planet. Agriculture stands as a primary beneficiary of soil, benefiting from its ability to supply vital nutrients and a stable environment for plant development. Moreover, soil acts as a buffer, facilitating the dilution of pollutants and excess water, while also serving as a replenishment zone for groundwater [**Chen, Z. and Shah, T.M., 2019**]. Secondary uses for soils include components in confectionaries, insecticides, and toners. It also acts as a carbon sink, storing and cycling carbon, which helps mitigate climate change impacts (**Lal, R. 2020)**.

Common problems in the soil of India:

1. **Soil erosion** is the elimination of soil by natural forces, especially by wind & water, and it happens more rapidly than the soil-forming process can replace it **(Wolman, M.G., 2015).**
2. **Desertification** is the expansion of desert-like conditions in arid/semi-arid regions due to human interference or climatic changes **(Dregne, H.E., 2020)**
3. **Salinity in the soil** is due to excess irrigation in the irrigated areas and Alkalinity is indicated by the influence of sodium salts **(Bo Yu, Gang Peng, et al., 2015).**
4. **The effect of Industrialization** is gradually taking away a significant amount of land area from agriculture, forestry, and wild vegetation. **(Khademi, H et al., 2019).**

This is why there was a requirement of Sustainable and Eco-Friendly Soil Management System. The need for biological treatments for soil arises from the limitations and drawbacks of physicochemical treatments. Physicochemical treatments, while effective in remediating soil, can be expensive, laborious, and destructive to soil functionality. These treatments often involve the use of chemicals or mechanical processes that may have negative impacts on the environment (**Aparicio, J.D. *et al.* 2022**). Therefore, Biological treatments offer a sustainable option for soil remediation, as they rely on natural processes and microorganisms. They can help restore soil health and ecosystem services by promoting the breakdown and removal of contaminants (**Rafael G. Lacalle, José M. Becerril, Carlos Garbisu., 2020**). This can be done by various methods, most common and effective of them by using Microbial Biopolymers, which are explained further.

What are Biopolymers?

Biopolymers are naturally occurring organic substances. These are large macromolecules comprising several repeating units. These are biocompatible and biodegradable, which is why they are suitable for various purposes **(Thuo, M. *et al.*, 2021).** Such as in Food industry they are used in the edible films and packaging materials for products. In medical Field they are used in medical implants, tissue scaffolds and for wound healing in the pharma industry. Biopolymers have provoked a lot of attention in multiple of applications that involve environmentally friendly and ecological solutions. (**Varma, K. and Gopi, S., 2021)**.
Biopolymers are synthesized within living beings, particularly microorganisms, via the action of processive enzymes which help the linkage of fundamental building blocks such as carbohydrates, amino acids, or hydroxy fatty acids to form high molar mass compounds. These enzymes are critical in the biosynthesis of biopolymers, allowing the generation of complex molecular structures required for the proper functioning and development of living organisms. **(George, A. et al, 2020)**.

How does Biopolymers affect Soil?

Biopolymers have a profound impact on enhancing soil quality through their influence on physical, chemical, and biological properties. One key contribution is their ability to improve soil structure and aggregation, resulting in enhanced water infiltration, moisture retention, and root penetration. By utilizing biopolymer-based soil conditioners, significant advancements have been observed in soil porosity and aggregate stability, leading to increased water-holding capacity and decreased erosion risks. These beneficial effects contribute to overall soil health and sustainability. (**Weng, Z., et al., 2022**). Moreover, biopolymers serve as natural chelating agents, playing a role in enhancing nutrient availability and uptake for plants. They possess the ability to sequester and release vital micronutrients like iron, zinc, and copper, thereby contributing to improved soil fertility. By acting as effective mediators in nutrient interactions, biopolymers support plant growth and development, ultimately benefiting agricultural productivity. (**Bamatov, I.M., Rumyantsev, E.V. and Zanilov, A.K., 2019**). Furthermore, the application of biopolymer-based soil amendments has shown to have a positive impact on microbial activity and biodiversity within the soil. This promotes their growth and activity, resulting in improved circulation of nutrients, organic matter breakdown, and the eradication of soil-borne diseases. In conclusion, the use of biopolymers holds great promise for sustainable soil management and agricultural practices, supporting soil health and productivity.

2. MICROBIAL EXOPOLYSACCHARIDES (EPS)

Microbial exopolysaccharides (EPS) are a type of biopolymer produced by a wide range of microbes such as bacteria, molds, and yeasts. EPS (Extracellular Polymeric Substances) is a broad term that encompasses both biopolymers and biofilm production by microbes (**Sajna, K.V. et al, 2021**). They are generated as an exchange of energy mechanism when subjected to environmental signals (**Flemming, H.-C., & Wuertz, S. 2019**). In addition to providing protection to microbes, microbial biopolymers also serve as a storage reservoir for food materials within the organisms themselves. They possess unique properties, including essential biological activities, the ability to crystallize, and they have extremely high molar mass that can reach many millions.

The backbone of EPS is made up of repeating monosaccharide units classified as homopoly-saccharides and heteropolysaccharides. Individual sugars such as pentoses (arabinose and xylose), hexoses (glucose, galactose, mannose), amino sugars (glucosamine and galactosamine), constitute homopolysaccharides. Strong 1,4-- or 1,3--l linkages interconnect these sugars, as do more adaptable 1,2- or 1,6- linkages. On the other hand, Heteropolysaccharides contain up to three distinct kinds of sugar units that are repeated across their structure. Carbohydrates can be attached to protein molecules (glycoproteins), lipids (glycolipids), acids (galacturonic acid, or mannuronic acid), and possibly extracellular DNA. The incorporation of different sugars and their connections to other molecules like proteins, lipids, and acids enhance the versatility and potential functions of EPS in various biological processes. (**Shukla, A., et al., 2019**). The EPS serves critical functions for the microbial cell, including protection from both abiotic and biotic stress (**Limoli et al. 2015**).

Function of EPS in soil:

Microbial EPSs enrich the quality as well as the fertility of soil. EPS's high-molecular-weight polymers aid soil bacteria in attaching to the outside of soil particles and preserve the collected particles (**Costa OYA, et al., 2018**). EPSs adhere to soil surfaces through various mechanisms such as hydrogen bonding, cationic bonds, anion adsorption, and van der Waals forces. This organic outcome of EPS adherence plays a crucial role in influencing soil properties and processes. One significant effect of EPS adherence is the reduction of soil wetting and swelling. This phenomenon contributes to the firmness of soil aggregates, improving aeration, permeability, and root penetration while reducing runoff.

By binding to soil particles, EPS enhances the micro aggregation of soil, resulting in the formation of an organo-mineral sheath. This sheath improves the soil's foundation while providing stability to the soil regardless of stressful conditions. The presence of EPS in the soil matrix creates a supportive network that enhances soil stability and prevents soil erosion (**Bettermann, A., et al., 2021**). It acts as a binder, effectively holding soil particles together and reducing the risk of structural degradation. This, in turn, promotes better soil water retention, nutrient availability, and overall soil health. The adherence and accumulation of EPS in the soil not only influence physical properties but also have implications for microbial activity and nutrient cycling. EPS can serve as a substrate for beneficial microorganisms, supporting their growth and activity. This, in turn, contributes to the disintegration of organic matter, nutrient transformation, as well as overall soil fertility (**Costa OYA, et al., 2018**). Many PGPB of the rhizosphere preserve plant-water relations, ion homeostasis, and photosynthetic efficiency in drought and salt-stressed plants. Stress reduction requires a complicated signaling network that is activated by plant-microbe interaction (**Yang, J., et al., 2009**). Therefore, EPS acts as a nutrient mediator and an adhesive a scaffold for attaching microbes to plants, and it is a significant moderator for sustaining plant health in the face of abiotic stress.

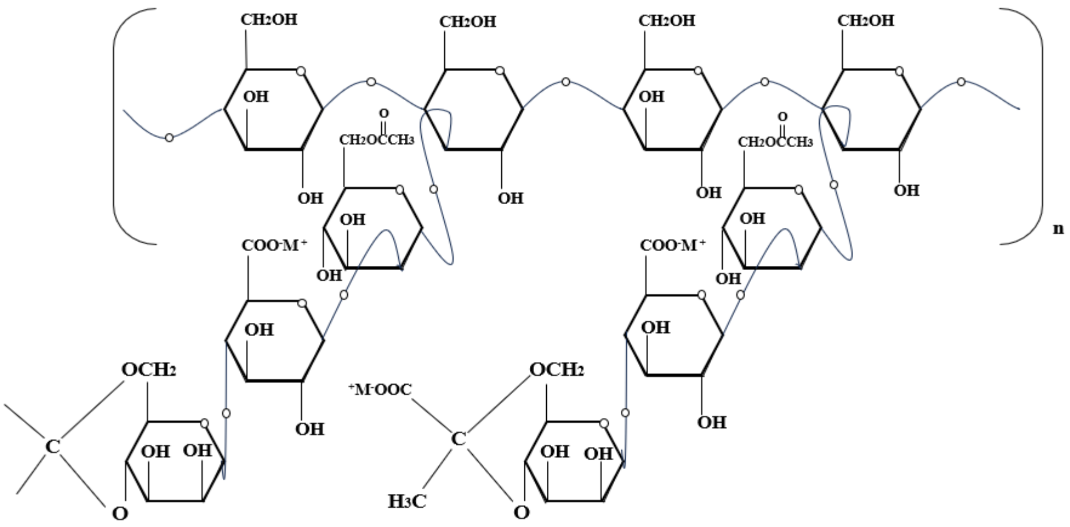
3. TYPES OF MICROBIAL BIOPOLYMERS:

Biopolymer	***Microbe used***	**Chemical Composition**	**Advantages**	**References**
Cellulose	*Acetobacter xylinus*	$(C_6H_{10}O_5)_n$	Excellent water holding capacity. Improve soil structure by formation of soil aggregates.	**Syakir, M.I. *et al.* (2021)**
Xanthan Gum	*Xanthomonas campestris*	$C_{35}H_{49}O_{29}$	Reduction in permeability. Retention of water due to strong hydrogen bonding.	**Oliveira, P.J. and Reis, M.J. (2023)**
Gellan Gum	*Sphingomonas elodea*	-	Improvement of durability of soil and soil strengthening	**I. Chang, et al., 2015.**

			Enhancement in soil's shear strength	
Curdlan	<u>*Agrobacterium biobar, Alcaligenes faecalis*</u>	$(C_6H_{10}O_5)_n$	Ability to retain nutrients in soil. Ability to stabilize soil's pH.	**Yuan, M., et al., 2021.**

Table-I: Biopolymers and their uses

3.1. XANTHAN GUM



Chemical Structure of Xanthan Gum

COMPOSITION:

Xanthan gum is a polysaccharide developed by *Xanthomonas campestris* through a process known as aerobic fermentation. It is made up of a main chain linked by -1,4-glycosidic bonds and a trisaccharide side chain made up of three different monosaccharides: glucose ($C_6H_{12}O_6$), mannose ($C_6H_{12}O_6$), and glucuronic acid ($C_6H_{10}O_7$). This sugar composition is repeated in the structure of xanthan gum. (geo) Xanthan gum is an exocellular polysaccharide derived from glucose or sucrose fermentation. It is made up of five sugar residues that are repeated in its structure: two glucose units, two mannose units, and one glucuronic acid unit. **(Tran et al. 2017).**

PRODUCTION:

The manufacturing of xanthan gum is an intermittent process that takes place at pH 7.0, 28°C, and with elevated agitation rates (400-800 rpm) **(Habibi and Khosravi-Darani 2017).** The biosynthesis of xanthan gum begins with the absorption of carbohydrates, that take place through two techniques either active transport of carbohydrates or their facilitated diffusion. Using a hexokinase enzyme that utilizes adenosine 5'-triphosphate (ATP), the substrate is phosphorylated. This phosphorylated substrate is additionally transformed to different sugar nucleotides through enzymatic reactions, such as UDP-Glcpyrophosphorylase. Specific sugar nucleotides, including UDP-glucose, GDP-mannose, and UDP-glucuronic acid are essential for the synthesis of xanthan gum. The enzymes associated with the biosynthesis pathway facilitate the transformation of the phosphorylated substrate into these essential sugar nucleotides, enabling the synthesis of xanthan gum with the suitable repeating unit **(Alhalmi, A., et al (2017).** In industrial production, the most commonly used primary carbon sources, for the production of xanthan gum are Sucrose and Glucose. The concentration of carbon sources is critical in improving the manufacturing mechanism.

During the resting stage/stationary phase of bacterial growth, xanthan gum is produced. Precipitation and recovery steps, typically involving acetone or alcohols, are involved in the downstream process of xanthan gum production. These substances are used to induce the precipitation of xanthan gum from the fermentation broth. The addition of acetone or alcohols causes the xanthan gum to separate from the liquid phase, allowing for its recovery. Additionally, heat treatment is a crucial step in the downstream process. Heat treatment helps eliminate the pathological nature of the bacteria, ensuring the safety and quality of the final product. **(Bhat, I.M., et al., 2022).**

PROPERTIES

Even in small quantities, xanthan gum (XG) exhibits a significant increase in the viscosity of water. This is attributed to its hydrophilic nature, which allows it to adsorb water molecules and form hydrogels, leading to increased viscosity **(Chang et al., 2015).** The trisaccharide chain, associated to the β-D glucan backbone, contributes to the consistency and strength of xanthan gum. Xanthan gum demonstrates pseudoplastic behaviour, meaning its viscosity decreases under shear stress and recovers when the stress is removed. Furthermore, xanthan gum is known for its stability over a wide range of pH and temperature conditions. It can maintain its viscosity and functionality under various pH levels and temperature fluctuations**. (Bagheri, P., et al., 2023).** Its anionic and hydrophilic properties are frequently utilized to thicken drilling fluids to increase drilling efficiency **(Latifi et al. 2016).**

APPLICATIONS:

1. Ability to retain water: Xanthan gum exhibits an exceptional capacity for binding water, surpassing other microbial polysaccharides in this regard, making it a particularly fitting choice for employment as a Superabsorbent Polymer (SAP) (Dehghan et al., 2019). It can help to ameliorate drought stress of plants and reduce erosion. Xanthan gum when interacts with water it undergoes hydration. The individual Xanthan Gum molecules absorb water and swell, forming a gel-like structure. **[Berninger, T., Dietz, N., & González López, Ó., 2021].**

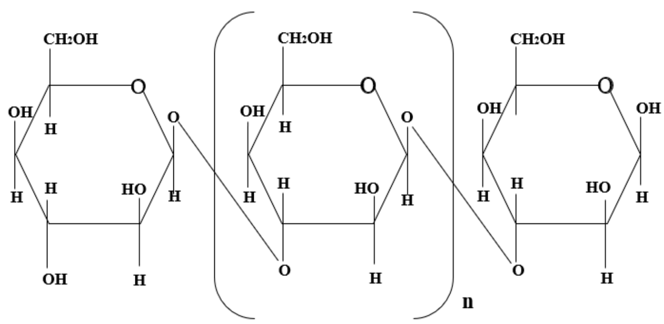
2. Strengthening of Soil structure: Xanthan gum can help soil to get denser structure, which helps in reduction of repulsive forces and increases surface resistance. This is done as the Xanthan Gum molecules disperse within the soil, the gel's strands intertwine with soil particles forming aggregates. As these aggregates are large clumps of soil they are more stable and less prone to break apart, hence strengthening the soil **[Bagheri, P., Gratchev, I., & Rybachuk, M., 2023].**

3. Long term impacts: Xanthan Gum's effect of soil structure can be long-lasting. Over time the improved aggregation and porosity can contribute to healthy soil making it resistant to degradation. [**Mendonça, A., Morais, P. V., Pires, A. C., Chung, A. P., & Oliveira, P. V. (2020)].**

4. Improving shear-strength: Recent studies have shown the good performance of xanthan gum used in soils. The significant factors enhancing shear strength and reducing hydraulic conductivity in soil improvement include soil type and density, hydration level, mixing technique, and void ratio. These parameters collectively play a pivotal role in dictating the efficacy of biopolymer application within the field. Anticipated outcomes include the establishment of strong hydrogen or electrostatic bonds, primarily influenced by the strength of xanthan gum, between its monomers and soil particles [**Mendonça, A., Morais, P. V., Pires, A. C., Chung, A. P., & Oliveira, P. V. 2020**]. The addition of xanthan gum to soil has been shown to increase its compressive strength, cohesion, and water holding capacity.

5. The experimental investigation done by Sujatha et al. (2022) demonstrate that as the content of xanthan gum increases, the modification in dry weight with increasing water content becomes negligeable as compared to untreated soil. This indicates that Xanthan Gum minimize the sensitivity of soil to moisture fluctuations. This effect becomes more distinctive as the percentage of Xanthan Gum increases, which can be credited to the development of a complex system of interconnected hydrogen bonds and cross-links. This network enhances the stiffness of the soil matrix and improves its resistance to compaction.

3.2. CURDLAN GUM



Chemical Structure of Curdlan

COMPOSITION:

Curdlan, derived from microorganisms, has distinctive characteristics, particularly its ability to withstand high temperatures, which is referred to as thermal gel. Curdlan's primary component is glucose, which is linked together via (1-3)-β-glucose linkages to form a linear, molecular homopolymer (**Aquinas, N., et al., 2022**). Curdlan synthesis has previously been shown to occur with the help of the reagent Uridine-diphosphate-glucose phosphorylase, which converts Uridine-diphosphate-glucose to curdlan. The occurrence of sources of carbon in the growth medium causes bacteria to secrete enzymes that break down sugars and convert them to curdlan (**Yuan, et al., 2021**).

PRODUCTION

Among the various genera, Agrobacterium is recognized as the primary producer of linear curdlan, specifically (3-1)-glucan, which can exhibit some branching with sugar units connected through (1→3,1→6) linkages (**Venkatachalam, et al., 2020**). Initially discovered in Alcaligenes faecalis, curdlan production occurs in the presence of extracellular exogenous sugars (**Prakash, S.; Rajeswari, K., et al., 2018**).

PROPERTIES:

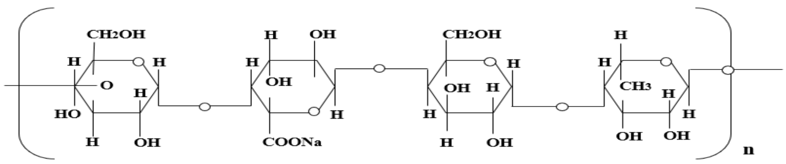
Curdlan is distinguished by a number of important characteristics. It is a resinous substance that can crystallize at high temperatures and has a high-temperature resilience. It has no color, flavor, or odor. It is easily soluble in alkaline fluids with a pH of 12 or higher, such as NaOH and Na_3PO_4, but unable to dissolve in water, alcohol, and acidic solutions. Despite being insoluble in water, curdlan can form gels when heated (**Jia, Xiaoyu; Wang, Cheng et al., 2021**).

Another notable property is its water-absorbing capacity, enabling it to bind water and prevent separation. Its outstanding durability throughout industrial procedures such as frying and freezing, as well as its solubility characteristics, add to its utility (**Aquinas, N., et al., 2021**).

APPLICATIONS OF CURDLAN GUM

Because of its favorable physical and chemical properties, curdlan, a significant microbial sugar, finds wide-ranging applications in the food industry, industrial, and healthcare sectors. It is considered to be environmentally friendly, making it suitable for various industrial uses such as thickeners, stabilizers, and agents. Curdlan's ability to crystallize is also used in food products, and it has biological properties such as an antioxidant and prebiotic activity (**Mangolim, C. S., da Silva, et al., 2017**).

3.3. GELLAN GUM:



Chemical Structure of Gellan Gum

COMPOSITION:

Gellan gum, a form of polysaccharide family member, is a high-molar-weight polymer synthesized by *Sphingomonas elodea* (**I. Chang and G.-C. Cho, 2018**). The structure is composed of four molecular units: (1,3)-β-D-glucose, (1,4)-β-D-glucuronic acid, (1,4)-β-D-glucose, and (1,4)-α-L-rhamnose. (**I. Chang, A. K. Prasidhi, J., 2015**).

PRODUCTION:

The fermentation process for gellan gum production typically occurs at a temperature of 30℃, within a pH range of 6.0-7.0. The fermentation time ranges between 30 and 60 hours, with blending at a speed of 250 rpm. Following fermentation, alcohol is used to dissolve the gellan gums, and the parameters of extraction can be adjusted to acquire the gum with various levels of esterification. It's production is directly linked to the development of microbes, and variables which inhibit microbial growth can result in a reduction in production. Yeast extract is utilized as a source of Nitrogen & sucrose as a source of Carbon. It is known to provide optimal conditions for maximizing gellan gum production (**Chang, I., Cho, GC., 2018**).

PROPERTIES:

A research study looked into the ability of gellan gum to minimize permeability and strengthen shallow soils. Furthermore, a recent study focused on understanding the interactions linking gellan gum & soils. It was investigated by Chang and Cho that the shear strength and cohesiveness of sand-clay blends treated with gellan gum using direct shear tests which revealed that as overburden stress increased, so did shear strength and cohesion (**West, T.P., 2021**)

APPLICATIONS:

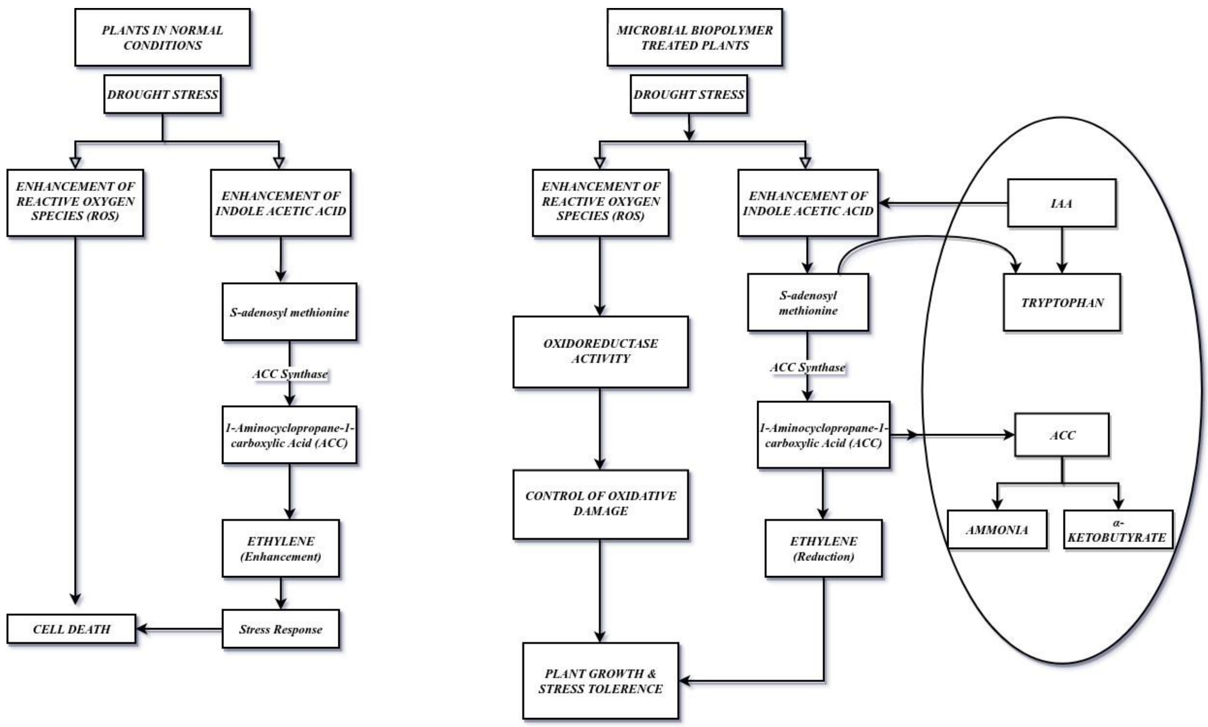
Chang, I., Im, J., and Cho, G.-C. (2016) found that gellan treated sands displayed significant strengthening even at small amounts as a renewable biopolymer utilised for soil improvement. Furthermore, application of gellan has been shown to be effective in decreasing sand permeability because of to the pore filling effects of gellan hydrogels. When gellan gum is applied to soil, the reduction in permeability is almost immediate; thus, when employed as a permeability-controlling barrier, gellan gum can serve as a quick alternative to sufficiently reduce soil permeability.

4. ROLE OF MICROBIAL BIOPOLYMERS IN SOIL TREATMENT

4.1. In Drought stress

Drought has a major impact on global warming worldwide, and it minimizes microbial operations that are crucial for sustainability of the ecosystem as well as cultivation of crops **(Schimel, J.P., 2018).** It has everlasting effects on soil microbiome, as it causes plantation to shift to more drought-tolerant plant species, which then identifies root-associated microorganisms Plant growth-promoting bacteria (PGPB) perform a major part against abiotic stresses in the environment. PGPB are regarded as a harmless and environmentally friendly alternative to the shortage of food supply problem. **(Abdelaal, K. et al, 2021).** Extended breeding programmes and genetic manipulation are two factors required to produce drought-tolerant varieties with high crop yields and acclimatization for various geographical regions **(Martignago, D. et al, 2020)**. The mechanisms of the crops which have much improved drought tolerance include antioxidant defenses & osmotic regulation which is performed by accumulation of complementary solutes. It also includes the synthesis of 1-aminocyclopropane-1-carboxylate (ACC) deaminase an exopolysaccharide (EPS), synthesis of plant hormones, and defense tactics like pathogenesis-related gene expression **(Vurukonda, S.S. *et al.*, 2016)**.

Ilyas et al. demonstrated the function of EPS-producing microbial strains in drought stress reduction in wheat grain, demonstrating that *Azospirillium brasilense* and *Bacillus subtilis* generated a large amount of Exopolysaccharides. This increased the resistance of plant to drought despite drought stress. The combination of these strains of bacteria led to a significant increase in EPS and proline production, as well as an increase in the level of stress-triggered plant hormones. **(Ilyas, N. *et al*, 2020)**.



Pictorial representation of the mechanism of biopolymer treated plants.

4.2. Anti-Desertification

It is a long-standing theory that soil erosion behavior is determined by the porosity of soil particles (that is, if it is free or tightly placed) and the moisture content of soil **(Iverson, R.M. *et al.*, 2000)**. Various rain exposures result in different volumes of water within the soil gradually, that is important for understanding soil erosion resistance. It was studied by Chang et al. **(Chang, I. *et al.*, 2015)** that as the water content of soil raised so did the soil's erosion ratio. For this purpose, they conducted an experiment with raw untreated soil and Biopolymer-treated soil. Short-term precipitation effects on both types of soils were investigated. Irrespective of the original water quantity and surface vegetation present in the environment, biopolymer-treated soils demonstrated lower erodibility or higher erosion resistance than untreated natural soil during short-term precipitation. The biopolymer-treated soils' erosion tendency remained steady. This can be defined as a combination of the protective coating affect and bio-compound-induced enhancing of soil interparticle association. The mechanism includes Microbial biopolymers have a high water-holding capacity, which enables them to retain water. When they come into contact with water, they begin to absorb the precipitation, forming hydrogels with a high degree of swelling. Because of their hydrophilic surface properties, biopolymers form strong hydrogen bonds with water molecules **(Soldo, A., et al., 2020)**. Since there was no such binding in the natural soil, its erosion ratio was greatly influenced by its original quantity of water, whereas the erosion ratio of the biopolymer-treated soils was still relatively minimal and steady regardless of soil moisture increment.

4.3. Strengthen soil:

Biological approaches such as Microbial induced carbonate precipitation (MICP) are an efficient method of increasing soil strength and its burden-holding capacity **(Zhang, K. *et al*, 2023)**. MICP is a novel and promising ground improvement technique which involves bacterial precipitation of Calcite in situ condition. It entails urea hydrolysis in the presence of the Urease enzyme, which is secreted by soil-based urease-producing bacteria.

However, these involve introducing a massive microbial community as well as cementing reagents into the soil to create a specific improved environment for the microbes where they can thrive. **(Castro-Alonso, M.J. *et al*, 2019.)**. Therefore, soil improvement with biopolymers is a more tempting option than MICP because it doesn't require the culturing of microorganisms in the soil. Biopolymer treatment, unlike MICP, can also be used to improve fine-grained soil **(Ashraf, M.S. *et al*, 2017)**. They also have an advantage over MICP because they don't necessitate nutritional inoculation and can be utilized entirely for bettering the soil.

The study done by (**Chen, C., Wei, K., Gu, J., Huang, X., Dai, X., & Liu, Q. (2022**) investigates the combined use of an eco-friendly biopolymer and fiber inclusions as an alternative to traditional cement for reinforcing soft soil. Unconfined compression tests were conducted to analyze the effects of biopolymer and fibers on various characteristics of soft soil. The findings revealed that the combination of biopolymer and fibers resulted in a higher compressive strength than using each material individually. Biopolymer-enhanced soil strength becomes more prominent with longer curing times. The biopolymer contributes to peak strength and brittleness improvement, while fibers reduce brittleness and enhance ductility. It is proven that fibers restrain crack development and biopolymer enhances soil particle bonding. The study indicates that the combined effect of biopolymer and fibers is more complex than the sum of individual effects and suggests a promising avenue for sustainable soil reinforcement.

4.4. Salt tolerance

The global issue of rising soil salinity has sparked an alarm, owing primarily to the excessive utilization of chemical-based fertilizers and pesticides, insufficient water drainage, and inefficient irrigation practices. The excessive amount of salt in the soil causes significant crop damage. (**Deng J, Orner EP, et al., 2015**). Extracellular polymeric substances (EPS) in various forms and quantities are produced by strains that exhibit salt stress tolerance, enhancing seed germination and crop production under stressful atmospheric conditions (**Susilowati A, et al., 2018**). Microbes, particularly bacteria, have a capability to confer salt resistance on plants and boost their development in saline soil via a variety of mechanisms.

EPS binds to sodium ions, thereby preventing their movement from the soil to the plant shoot, and therefore reduces absorption of Sodium from the soil, thus mitigating the outcomes of high soil salinity. This helps maintain the Na+/K+ balance in plants, enabling them to survive in unfavorable soil conditions (**Singh RP, Jha PN, 2016**). EPS chelation of sodium ions around the roots prevents their upward movement and decreases sodium absorption by the plant stem [88]. According to research, microbial polymers perform a significant role in overcoming salt stress not merely for the microbes but also for surrounding plant life. By entrapping and reducing the number of charged particles, polymers produced by salt-resistant strains can decrease sodium absorption by plants (**Upadhyay, et al., 2011**).

However, it has been observed that when S. meliloti strain EFBI cells are inoculated in a low salt concentration medium, EPS production is significantly reduced. This particular strain was obtained from the cysts of a particular species of plant evolving in a marshy area with an overall salinity of 0.3 M, indicating that even low levels of salt can be stressful. The study did not go into detail about how EPS could be used for survival and symbiosis in this context (**Costa, et al., 2018**).

Table III: Bacteria used for Salt Tolerance

Microorganism	**Crops**	**Properties**	**References**
Rhizobium meliloti	Tomato	Increase soil aggregation and biofilm formation	**Wang DC, et al., 2019.**
Bacillus sp.	Wheat	Rhizospheric aggregation of soil. Reduction in Sodium uptake and formation of root biofilm.	**Upadhyay SK, Singh J S, Saxena A K, Singh D P. 2012.**

5. A DIFFERENCE BETWEEN THE TRADITIONAL METHODS AND RECENT METHODS OF SOIL IMPROVEMENTS

PROPERTIES	**Microbial Biopolymers**	**Traditional Soil Treatment Methods**	**REFERENCES**
Impact on Environment	Biodegradable and environmentally friendly.	Cement, the most commonly used material, is responsible for heavy greenhouse gas emissions.	(Soldo, A., Miletić, M. & Auad, M.L., 2020) (Chang, I., Im, J. and Cho, G.-C. 2016)
Soil Stabalization	Can prevent soil erosion and promote soil stabilization.	Limited biodegradability and potential for long-term environmental persistence.	(Chang, I. *et al.* (2015) (Chang, I., Im, J., & Cho, G.-C. 2016)
Improvement in soil properties	Enhance soil mechanical properties, such as bearing capacity and shear strength.	May require extensive excavation and construction processes.	(Soldo, A., Miletić, M. & Auad, M.L., 2020) (Chang, I., Im, J., & Cho, G.-C. 2016)
Productivity	Potential to improve the productivity of agricultural land.	Cannot improve the productivity of land.	(Aparicio, J.D. *et al.* 2022)

6. CHALLENGES OF IMPLEMENTING MICROBIAL BIOPOLYMER BASED SOIL TREATMENT:

1. **Sustainability**: Assessing the long-term impacts of microbial biopolymer treatments on soil, water, and ecosystems is complex. Ensuring that these treatments are sustainable and do not cause unintended environmental consequences requires thorough monitoring and research [Chang, I., Im, J., & Cho, G.-C. 2016].
2. I**ntegration into existing agricultural practices**: Incorporating microbial biopolymer treatments into existing infrastructure and practices may require modifications or adaptations. Compatibility issues and potential conflicts with conventional methods can impede seamless integration. [**Chang, I. *et al.* 2015**]
3. **Cost**: The production of microbial biopolymers can be resource-intensive, requiring specific cultivation conditions and raw materials. Scaling up production while maintaining affordability can be challenging, especially for large-scale applications. [**Chang, I., Im, J., & Cho, G.-C. 2016**].
4. **Limited research**: While microbial biopolymer treatments show promise, there is still a need for extensive research and data collection to demonstrate their effectiveness, especially in real-world scenarios and diverse soil types [**Armistead, S. J., Smith, C. C., & Staniland, S. S. 2022**].

Therefore, even though microbial biopolymers offer a sustainable and environmentally friendly approach to soil treatment, there are still challenges associated with their implementation. Addressing these challenges will require continued research and development, as well as collaboration between researchers and farmers.

7. CONCLUSION

Microbial biopolymers can perform a significant part in improving soil strength and productivity. Biopolymers are naturally occurring polymers synthesized by microorganisms, such as bacteria, fungi, and algae, and are composed of organic molecules such as proteins, carbohydrates, and lipids. One of the main benefits of microbial biopolymers is their ability to improve soil structure. They can increase soil porosity, water-retaining capacity, and nutrient availability, all of which are essential for nutritious plant growth. Biopolymers can also enhance soil aggregation, which helps to prevent erosion and improve soil stability. In addition, microbial biopolymers can facilitate the upsurge in diversity and activity of soil microorganisms. This is because they serve as a basic resource of nutrients and energy for soil microorganisms, which consecutively can support in the development of valuable microorganisms such as nitrogen-fixing bacteria and mycorrhizal fungi. This leads to improved nutrient cycling, disease suppression, and overall soil health. Finally, microbial biopolymers can also help to reduce soil erosion and water runoff. Improving soil structure and stability can help prevent soil particles from being washed away during heavy rain events, reducing soil erosion and nutrient loss. Overall, the use of microbial biopolymers can be an efficient approach for improving soil well-being and productivity. They can promote soil structure, enhance microbial diversity, and reduce soil erosion, all of which are essential for healthy plant growth and sustainable agriculture.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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