J Biochem Technol (2025) 16(3): 51-62
https://doi.org/10.51847/RQGqjwM4nG
ISSN: 0974-2328

Exploring the Potential of Microbial Exopolysaccharides as Innovative and Eco-Friendly Cleansing Agents: A Review

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Received: 06 May 2025 / Received in revised form: 03 August 2025, Accepted: 14 August 2025, Published online: 29 August 2025

Abstract

Microbial exopolysaccharides (EPS) are high molecular weight carbohydrate polymers secreted by bacteria, fungi, and algae, representing an important class of bio-based materials with wide ranging industrial and environmental applications. These polymers are broadly classified into capsular polysaccharides, which remain tightly bound to the microbial cell surface, and slime polysaccharides, which are released into the extracellular medium. The structural diversity of EPS, determined by variations in monosaccharide composition, glycosidic linkages, molecular weight, and functional group substitutions, confers unique physicochemical properties such as viscosity modulation, emulsification, flocculation, and gel formation. Such properties are further complemented by biological activities including antimicrobial effects, biofilm formation, metal ion chelation, and strong biocompatibility, rendering EPS suitable as environmentally friendly cleansing agents in diverse sectors. Beyond their inherent biodegradability and safety, microbial EPS hold promise as sustainable alternatives to chemical surfactants and synthetic polymers in cleaning formulations, wastewater treatment, soil remediation, and biomedical hygiene. This review critically examines the structural complexity, biosynthetic mechanisms, and multifunctional applications of microbial EPS, with particular focus on their emerging role as eco-friendly cleansing agents. It further explores optimization strategies, technological interventions, and future research directions needed to overcome production bottlenecks, improve scalability, and establish standardized evaluation protocols, thereby paving the way for their wider industrial adoption.

Keywords: Microbial exopolysaccharides, Cleansing agents, Antimicrobial activity, Biodegradability, Environmental remediation, Sustainable hygiene

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Introduction

Microbial exopolysaccharides (EPS) are heteropolymers of carbohydrates produced by numerous microorganisms that are known to possess a variety of biological activities and can serve as efficient cleaning agents. These polysaccharides can be divided into capsular polysaccharides that strongly bind microbial cell walls and slime polysaccharides released into the surrounding medium (Madhuri & Vidya Prabhakar, 2014; Ibrahim *et al*., 2022). Made up of homopolysaccharides or heteropolysaccharides, EPS has been studied and found useful for their applications in various industries, such as food, medicine, and environmental studies, showcasing the versatility and use of EPS in industrial and clinical settings (Madhuri & Vidya Prabhakar, 2014; Özatik *et al*., 2022; Wąsacz & Chomyszyn-Gajewska, 2022; Wang *et al*., 2023; Chakraborty & Rajasekar, 2024). The distinctive structural features of EPS, including their molecular weight, monosaccharide content, and branching structures, profoundly impact their functional properties. These features augment their biological activities, such as antimicrobial activity, biocompatibility, and biofilm-forming ability, which are essential for their effectiveness in cleansing applications (Madhuri & Vidya Prabhakar, 2014). From the literature, it is evident that EPS can suppress the growth of disease-causing microorganisms and hence are good candidates for application in personal care products and medical products designed to induce hygiene and avert infections (Nwodo *et al*., 2012; Ibrahim *et al*., 2022) **(Figure 1)**.

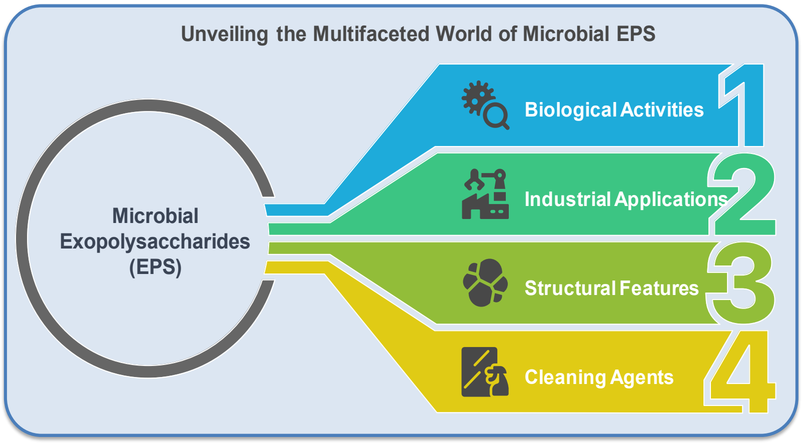

Figure 1. Unveiling the Multifaceted World of Microbial EPS

Though microbial EPS offers several benefits, like biodegradability and safety, its prospect as a cleaning agent is challenged by various factors, like inconsistency in research methods and production logistics at a large scale. The absence of standardized assessment procedures also makes it difficult to assess their efficiency, requiring thorough research to determine their mode of action and streamline production methods (Nwodo *et al*., 2012; Abdalla *et al*., 2021). With the growth of the literature on EPS, there is expanding interest in their multifunctionality and uses in environmental remediation, food processes, and pharmaceutical therapies (Ibrahim *et al*., 2022; Singh *et al*., 2025). Current technological developments have further supported the study of EPS, with a significant rise in publications reporting their uses (Abdalla *et al*., 2021). Advances in extraction techniques and a better comprehension of their structural properties hold great potential to tap the full capacity of microbial EPS as efficient, environmentally friendly cleaning agents in a wide range of industries. More research is needed, however, to overcome current limitations and provide assurance that these promising substances can be consistently applied in practical applications (Nwodo *et al*., 2012; Ibrahim *et al*., 2022). Due to their natural origin, microbial EPS are inherently biodegradable and pose minimal risk to human health and the environment, making them attractive for sustainable product development (Tiwari *et al*., 2024). Their application in green cleaning solutions is particularly appealing in the context of increasing environmental awareness and the demand for safer, non-toxic ingredients. However, several obstacles continue to limit their commercial use, such as inconsistent production yields, high processing costs, and the absence of standardized methods for performance evaluation. This current review focuses on overcoming these limitations by modifying microbial strains, improving fermentation processes, and broadening the scope of EPS use in industrial, medical, and cosmetic sectors.

Classification and Structural Characteristics of EPS

They may be classified into two types of secretions: capsular polysaccharides, which tightly adhere to the microbial cell wall to form a capsule, and slime polysaccharides, which are weakly attached or completely released into the extracellular environment. EPS can be homopolysaccharides, which include just one kind of monosaccharide, or heteropolysaccharides, which contain a range of monosaccharides such as glucose, galactose, and fructose, as well as less prevalent sugars such as rhamnose and mannose (Wang *et al*., 2023) **(Figure 2)**. The structural properties of EPS govern its biological action. Molecular weight, sugar concentration, glycosidic linkage, branching, and spatial organization are all important factors (Madhuri & Vidya Prabhakar, 2014).

Homopolysaccharides

Homopolysaccharides consist of one kind of monosaccharide unit, which leads to a less complex structure (Mouro *et al*., 2024).

- *Dextran*: Dextran is synthesized by many lactic acid bacteria and finds utility in food and pharmaceutical industries because it thickens and stabilizes.
- *Bacterial Cellulose*: This type of cellulose is produced by some bacteria, particularly Gluconacetobacter species, and is utilized in biomedical engineering due to its biocompatibility and high tensile strength.
- *Curdlan*: A β-1,3-glucan synthesized by Agrobacterium species, curdlan is used as a gelling agent in food and cosmetics.
- *Levan*: This fructan polysaccharide, produced by bacteria such as *Bacillus subtilis*, is prebiotic and possesses potential health benefits.

Heteropolysaccharides

Heteropolysaccharides are composed of various kinds of monosaccharide units, which are responsible for their complicated structures and multifunctional properties (Mouro *et al*., 2024).

- *Xanthan Gum*: Produced by Xanthomonas campestris, xanthan gum is extensively utilized in the food sector as a stabilizer and thickener due to its capability to sustain viscosity under different conditions (Ates, 2015).
- *Alginate*: Isolated from brown seaweeds and formed by some bacteria, alginate is prized for its gel-forming properties and is widely employed in wound dressings and drug delivery systems (Netrusov *et al*., 2023).
- *Hyaluronic Acid*: This polysaccharide is particularly known for its water-retaining capacity and is widely utilized in

cosmetic products and medical treatments for its regenerative properties (Ates, 2015).

- *Emulsan*: Emulsan is a biosurfactant produced by Acinetobacter species and can stabilize emulsions, hence finding application in food and cosmetic products.

All microbial EPS have distinct biochemical features that make them useful in a variety of industrial and medicinal applications, including cleaning products and other formulations (Ekpo *et al.*, 2023; Kwatra *et al.*, 2024). Bacterial strains, environmental factors, and microbial community dynamics all have an impact on EPS generation. Engineered Lactococcus lactis strains, for example, can produce excessive amounts of EPS. These polysaccharides are used as food thickeners and stabilizers, such as in yogurt (Mouro *et al.*, 2024). Importantly, EPS promotes biofilm formation, which improves nutrient retention and microbial growth, especially in low-nutrient conditions. Because they are biocompatible and perform a variety of activities, EPS has potential uses outside of food (Ibrahim *et al.*, 2022; Srivastava *et al.*, 2022; Nastro *et al.*, 2025).

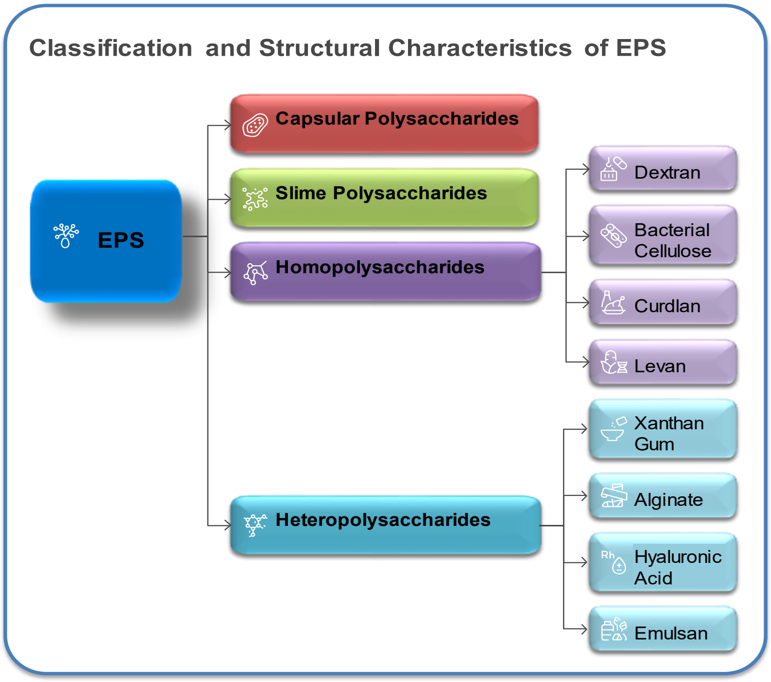

Figure 2. Classification and Structural Characteristics of EPS

Potential Application of Exopolysaccharides as a Cleansing Agent

Microbial EPS, bioactive polymers produced by various microorganisms, have garnered significant attention for their diverse applications across multiple industries. Their unique properties, such as biocompatibility, biodegradability, and high adsorption capacity, make them particularly suitable for use as cleansing agents (Tiwari *et al.*, 2024). This section explores the potential applications of EPS in cleansing, supported by insights from recent research. Further, a few types of EPS and their uses are listed in **Table 1 (Table 1)**.

Table 1. Different types of EPS, including their source and applications.

S. No	EPS	Source	Application	Reference
1	Welan	*Alcaligenes* bacterial species	Microbial EPS are utilized as eco-friendly thickening agents in the drilling industry to enhance fluid viscosity and drilling efficiency.	(Huang *et al*., 2022)
2	Azotobacter EPS	*Azotobacter Sp.*	Widely applied in the removal of oil contamination, microbial EPS enhances bioremediation by emulsifying hydrocarbons and improving pollutant breakdown.	(Sumbul *et al*., 2020)
3	Fungal EPS fraction	*Cordyceps Sinensis*	Used as immunomodulatory and antitumor agents by stimulating immune responses and inhibiting the growth of cancer cells.	(Zhang *et al*., 2005)
4	Mauran	Halophilic *Halomonas maura*	Serve as effective drug delivery carriers, offering targeted release and exhibiting cytotoxic activity specifically against cancerous cells.	(Natarajan *et al*., 2014)
5	Panettone	*Leuc. Mesenteroides*	Used as natural stabilizing agents to extend bread shelf life by retaining moisture and preventing staleness during storage.	(De Vero *et al*., 2021)

6	A succinoglycan-like EPS	*Rhizobium sp. PRIM17*	Prospective agent for bio-ink and its use in drug delivery	(Nagaraj & Rekha, 2023)
7	β-glycosidic sulphated heteropolysaccharide	*Bacillus subtilis*	As effective drug carriers in acidic environments by protecting active compounds and ensuring targeted, controlled drug release.	(Abdel-Wahab *et al*., 2022)
8	Pel EPS	*Pseudomonas aeruginosa*	Anti-biofilm agents	(Franklin *et al*., 2011)
9	Levan	*Bacillus mojavensis*	Prebiotics and sweeteners in dairy products	(Haddar *et al*., 2021)
10	Mutan	*Lactobacillus sp.*	Food additives, anticaries agents	(Ben-Zaken *et al*., 2021)
11	Alginate	Marine *Bacillus sp.,*	Immobilizing agent, microencapsulation material	(Han *et al*., 2020)
12	Hyaluronan	*Pseudomonas aeruginosa, Pasteurella multocida*	Moisturizing agents, pain reduction injections	(Sumayya & Muraleedhara Kurup, 2021)
13	Alteran	*Leuconostoc mesenteroides*	Used as microcarriers in cell culture systems, providing support for cell attachment, and large-scale cultivation.	(Zhang *et al*., 2022)
14	Inulin	*Limoslactobacillus reuteri, Lactobacillus gasseri*	Utilized as food additives, they act as prebiotic dietary fibers and exhibit anti-biofilm properties beneficial in food preservation.	(Xu *et al*., 2019)

Water Purification and Heavy Metal Removal

Exopolysaccharides have shown remarkable efficiency in the removal of heavy metals and other pollutants from contaminated water. For instance, a study on the EPS produced by *Klebsiella oxytoca* J7 demonstrated its ability to adsorb Ni^{2+} ions with a maximum capacity of 269.97 mg/g, following the Langmuir adsorption model (Ljubic *et al*., 2023). Similarly, microbial polysaccharides have been used as biosorbents for the removal of heavy metals and dyes from industrial effluents, offering a sustainable and cost-effective solution for wastewater treatment (Cheah & Ting, 2020; Blaga *et al*., 2021; Ramanaiah *et al*., 2023). The use of EPS in water purification is further supported by their ability to form biofilms, which can immobilize and degrade pollutants. Microbial biofilms, composed of EPS, have been successfully employed in bioremediation processes to remove environmental (Başar *et al*., 2022; Do *et al*., 2022; Kariri *et al*., 2022) pollutants (Vyas *et al*., 2022; Mogazy, 2023; Soni, 2024).

Personal Care and Cosmetic Applications

The emulsifying and stabilizing properties of EPS make them suitable for use in personal care products (İlhan *et al*., 2022; Yoong *et al*., 2022). For example, EPS produced by *Rhodosporidium babjevae* has been shown to exhibit emulsifying activity on sunflower oil, making it a potential ingredient in cleansing creams and lotions (Seveiri *et al*., 2020). Additionally, the antioxidant and anti-inflammatory properties of EPS, as reported in studies on *Lactobacillus plantarum* and other microbial strains, could be leveraged in the development of skin care products (Ates, 2015; Sajna *et al*., 2021).

Bioremediation of Environmental Pollutants

Rapid industrialization has made wastewater treatment from companies a major concern nowadays (Mohan *et al*., 2011; Chandrasekhar *et al*., 2021; Krishnamoorthy *et a*l., 2024). EPS have been widely investigated for their function in bioremediation, notably in the removal of heavy metals and organic pollutants from polluted settings (Chandrasekhar *et al*., 2021a; Dattatraya Saratale *et al*., 2022). Their capacity to function as biosorbents is due to their anionic charge, which aids in the sequestration of cationic pollutants. For example, microbial EPS may efficiently remove heavy metals such as cadmium and lead via electrostatic interactions, as shown in experiments where EPS had maximum adsorption capacities of 154 mg/g for cadmium and 250 mg/g for lead (Mohite *et al*., 2017; Vijaylakshmi *et al*., 2023).

Soil Remediation

EPS also plays a crucial role in soil remediation by immobilizing heavy metals and reducing their bioavailability (Narayana *et al*., 2025). Their ability to form complexes with metal ions prevents leaching into groundwater, thereby protecting both terrestrial and aquatic ecosystems. This application is particularly significant in areas contaminated with industrial pollutants, where EPS can act as a natural, eco-friendly alternative to conventional remediation techniques (Mohite *et al*., 2017; Vijaylakshmi *et al*., 2023).

Air Pollution Mitigation

In addition to water and soil, EPS has been explored for its potential to mitigate air pollution. For example, EPS-229, derived from microbial mats in the Moorea lagoon, has been shown to protect against urban pollutants such as PM2.5. This EPS forms a protective film on surfaces, limiting particle adhesion and facilitating their removal. When used as a cleansing agent, EPS-229 can trap and remove particles, making it an effective tool in combating air pollution (Borel *et al*., 2017).

Industrial and Cosmetic Applications

The versatility of EPS extends to industrial and cosmetic applications. In the textile and paper industries, modified EPS can act as biosurfactants, enhancing the biodegradation of organic pollutants and improving process efficiency. In the cosmetic industry, EPS-229 has been used to protect skin from urban pollutants, demonstrating its potential as a cleansing and protective agent in personal care products (Nastro *et al*., 2023) **(Figure 3)**.

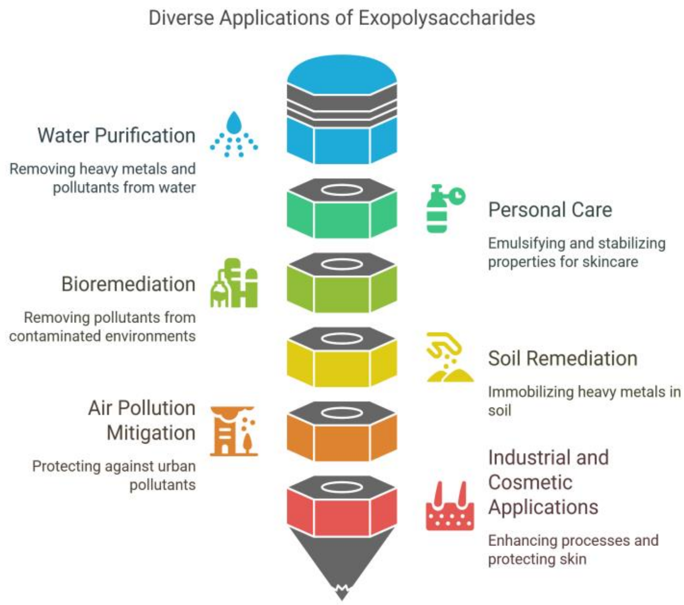

Figure 3. Diverse Applications of Exopolysaccharides

Advantages of Microbial Exopolysaccharides as Cleansing Agents

These polysaccharides are very hydrophilic and create a barrier on the surface of the skin that reduces water loss and improves hydration of the skin, which is especially suitable for people with dry or dehydrated skin (Schmid *et al*., 2015). The good water-binding capacity of EPS comes from their numerous polar groups, which engage in hydrogen bonds with water molecules, necessary for sustaining skin moisture levels. Apart from their moisturizing ability, EPS also has the important function of shielding the skin against environmental aggressors like pollution and UV radiation. Their anionic character enables them to bind with positively charged ingredients, offering a protective function that helps in the prevention of skin damage and premature aging (Schmid *et al*., 2015). This protective effect is also supplemented by the antioxidant nature of certain EPS, which can scavenge reactive oxygen species (ROS), thereby reducing oxidative stress on the skin (Nerd Skincare, 2024). In addition, the bioactivities of EPS are also affected by their molecular weight and conformation. Their versatility enables them to take on a range of structures in solution that can facilitate greater interaction with cells of the skin and extracellular matrix molecules like hyaluronic acid and collagen. Such interactions are important for facilitating repair and regeneration of the skin through stimulation of their synthesis (Nerd Skincare, 2024). The bioactivities of EPS can also be modulated by depolymerization methods that decrease the molecular weight of the natural polymers. This modification can enhance their functional properties and efficacy in cosmetic formulations to make them useful agents in skin care products. The various mechanisms of action of microbial EPS highlight their use as effective cleansing agents and skin care ingredients. Microbial EPS are increasingly being explored for their multi-faceted applications in a wide range of fields, most notably in biomedicine, food technology, and environmental cleaning. Microbially produced biopolymers, EPS provide a number of benefits as a result of their distinctive structural properties and bioactivities (Tiwari *et al*., 2024). Microbial EPS have emerged as promising alternatives to the conventional cleansing agents because of their special characteristics and advantages in skin well-being. In comparison to conventional surfactants that tend to remove the natural oils from the skin and destroy the skin barrier, microbial EPS are more gentle on the skin while imparting extra benefits to the skin **(Figure 4)**.

Hydration and Skin Barrier Protection

Microbial EPS provides several advantages as a cleanser, including its outstanding skin-hydrating potential. In contrast to traditional cleansers, which strip the skin of important lipids, producing dryness and irritation, EPS forms a protective, moisturizing barrier layer on the skin's surface. This barrier reduces transepidermal water loss, effectively storing moisture and maintaining adequate hydration levels. This is especially beneficial for those with dry, sensitive, or eczematous skin since EPS washes softly without compromising the skin's natural barrier function. The unique water-binding capacity of EPS results in a softer, more supple skin texture, making it an interesting element in future-generation skincare products (Schmid *et al*., 2015). Furthermore, the biocompatibility of EPS decreases the potential of allergic reactions or discomfort, making them excellent for those with sensitive skin.

Anti-Aging and Environmental Protection

In addition to hydration, microbial EPS provides essential protective functions against environmental stressors, distinguishing them from conventional cleansing products. EPS functions as a natural barrier against damaging UV radiation, a primary cause of premature skin aging, wrinkles, and even skin cancer. They also serve as a barrier against pollution, another key environmental aggressor that can harm skin cells and speed up aging (Schmid *et al*., 2015). By buffering against these stressors, EPS helps to preserve a youthful complexion and encourage long-term skin well-being. Conventional cleansers, though effective in their ability to eliminate dirt and grime, frequently fail to include these defensive attributes and even potentially enhance the damaging effects of environmental exposure by stripping the skin of its natural protections. The novel architecture of EPS enables them to form a breathable, protective barrier on the skin surface, serving as a first line of defense against environmental stress (Schmid *et al*., 2015). This additional protection renders EPS-based cleansers an important weapon in the fight against the visible signs of aging and maintaining skin health in the face of mounting environmental stress. In addition, the antioxidant function of certain EPS can also boost their protective effect by eliminating free radicals caused by UV radiation and pollution.

Biocompatibility and Skin Tolerance

One of the primary advantages of microbial EPS as cleaning agents is that they come from natural sources. Several EPS derived from various microbes are more biocompatible, reducing the chance of adverse responses when compared to synthetic cleansers. Because of their natural nature, EPS cleansers tend to have a milder contact with the skin, making them suitable for usage on a wide variety of skin types, from sensitive to acne. Microbial EPS has been demonstrated in studies to improve skin health without being irritating, which is important for persons with extremely reactive skin (Schmid *et al*., 2015).

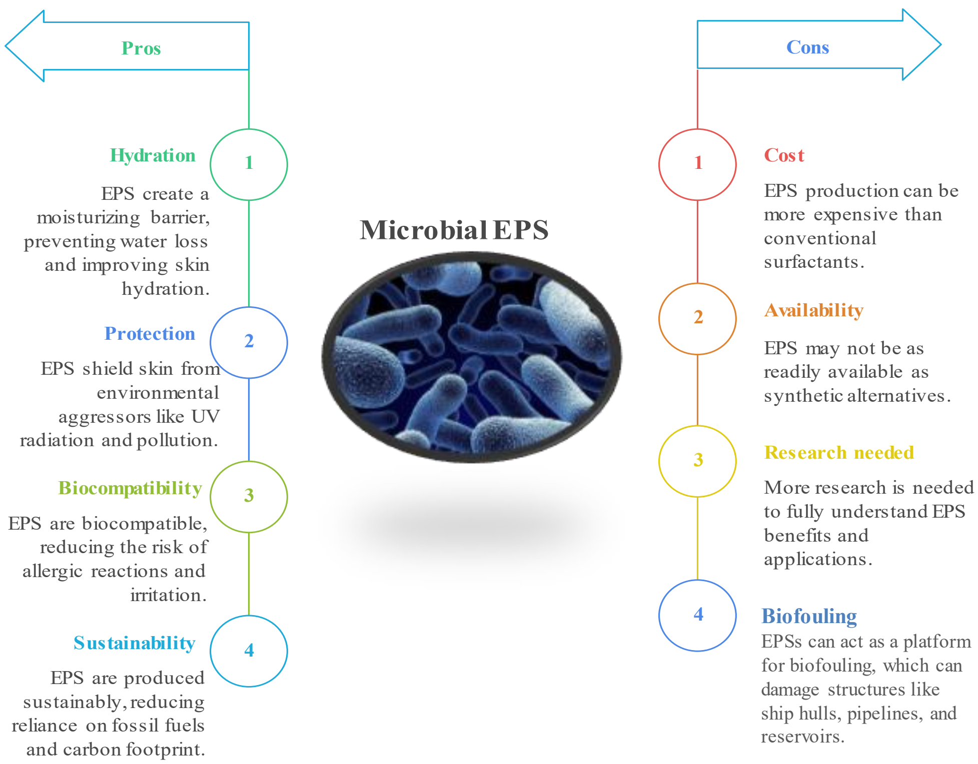

Figure 4. Pros and cons of Microbial Exopolysaccharides as Cleansing Agents

Conventional cleaning products, on the other hand, might include artificial ingredients, fragrances, or preservatives, which can serve as irritants or allergens and make any pre-existing skin problems like acne, eczema, or rosacea worse. The non-irritating character of EPS, combined with its capacity to maintain the skin's natural barrier function, positions it as an attractive alternative for individuals who want effective cleansing without damaging the skin (Schmid *et al*., 2015). In addition, the biodegradable nature of most naturally sourced EPS conveys compliance with increasing consumer demand for environmentally friendly products, another advantage over certain synthetic options.

Sustainability and Eco-Friendliness

Microbial EPS production provides a more sustainable and greener alternative to the conventional surfactant production process. As natural and green skincare products gain popularity among consumers, microbial EPS becomes a compelling option, catering to this new trend. Conventional surfactants are usually based on petrochemicals and pose negative environmental consequences in terms of production and waste disposal (Nastro *et al*., 2023). Conversely, most EPS are manufactured using fermentation processes and renewable materials, lessening dependence on fossil fuels and lowering the total carbon footprint (Schmid *et al*., 2015).

Such environmentally friendly production is appealing to ecologically minded consumers who wish to reduce their footprint. In addition, the biodegradability of most EPS reduces the fears associated with long-term environmental accumulation. By using EPS sourced from microbial origin, skincare products can minimize their reliance on artificial ingredients, thus adopting a greener and more sustainable skincare product development strategy (Schmid *et al*., 2015).

Challenges in the efficacy of Microbial EPS

The effectiveness of microbial EPS as cleaning agents poses various challenges **(Figure 5)** that must be overcome in order to completely utilize their potential. Although EPS can provide various environmental and health advantages, its perceived effectiveness against conventional cleaning agents tends to pose issues.

Misconceptions About Effectiveness

One of the biggest obstacles to the use of green cleaning products, especially those that contain sustainable ingredients such as EPS, is the common misperception that they are not as effective. Most customers think that these environmentally friendly substitutes are less effective than conventional cleaners, especially in removing stubborn stains and eradicating disease-causing microbes. Unfortunately, even if studies say that EPS can match conventional cleaners if applied correctly, doubts remain. This haunting skepticism not only influences consumer decisions in domestic cleaning but also restricts the application of EPS-based products in the industry (Paredes-Molina *et al*., 2025). Addressing this attitude is important in fostering green cleaning practices and paving the way for greater acceptance of environmentally friendly products in different contexts. Education and public awareness campaigns may be a key factor in reversing these mindsets.

Optimal Usage and Cleaning Techniques

The effectiveness of EPS-based cleaning solutions is mostly determined by the cleaning procedures used. Important aspects like application methods, contact duration, and the specific circumstances of the cleaning operation all have a significant impact on the overall outcome. For the most effective use of these ecologically friendly solutions, customers must be educated on their proper administration and inclusion in normal cleaning methods. Users may get better cleaning outcomes while also improving sustainability by learning how to utilize EPS-based chemicals properly. Proper training and knowledge may enable consumers and professionals to exploit the full capability of EPS products so that they are used to their greatest potential in various cleaning circumstances (Hasan *et al*., 2024; Paredes-Molina *et al*., 2025).

Environmental Conditions

Environmental conditions are instrumental in determining the effectiveness of EPS as a cleaning agent. Temperature fluctuations, pH levels, and the presence of interfering contaminants can have a great impact on the effectiveness of these substances. For instance, extreme temperature can change the chemical properties of EPS, and an inappropriate pH can interfere with their cleansing ability. Competing contaminants also interfere with the effect of EPS, making them less effective ("Green Cleaning Vs. Traditional Cleaning: Understanding The Key Differences," https://ecocleaning-nyc.com/green-cleaning-vs-traditional-cleaning-understanding-the-key-differences).

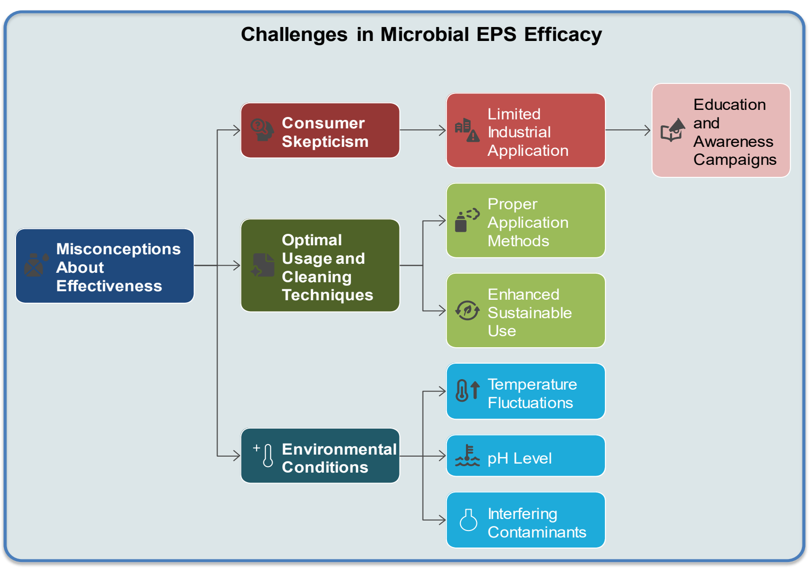

Figure 5. Challenges in the efficacy of Microbial EPS

Physical and Chemical Limitations

Microbial EPS plays a significant role in many environmental processes, especially in wastewater treatment and as a potential cleaning agent. Although helpful, EPS are also subject to many drawbacks, both physical and chemical. These may compromise their performance and effectiveness, and more research and development are needed to improve their application in many environmental situations and overall function.

Physical Limitations

One of the major physical constraints of EPS is their stability in changing environmental conditions. Temperature, pH, and availability of nutrients are some of the factors that can influence the structure and function of EPS. For example, environmental temperature influences bacterial growth and biofilm formation because higher temperatures may increase the hydrophobicity and adhesion capabilities of bacteria, which further change the composition of EPS. Additionally, the physical characteristics of EPS may be altered by environmental stresses, which could result in less effective performance in cleaning. The aggregation and flocculation capacity of EPS are also influenced by the concentration and composition of the materials. At high concentrations of EPS, gel-like structures could form that interfere with effective interaction with contaminants and, therefore, decrease the cleansing efficiency (Pan *et al*., 2016).

Chemical Limitations

Chemically, extracellular polymeric substances are complex mixtures whose composition may differ extensively, depending on the particular microbial community and prevailing environmental conditions. Their inherent variability makes it difficult to reliably predict their efficacy as cleaning agents. For instance, some chemical constituents of EPS might change their interactions with contaminants, with possible incomplete removal of contaminants. In addition, despite EPS being typically viewed as being environmentally friendly and biodegradable, their degradation products may in certain cases prove harmful or toxic based on the microbial processes that they undergo upon degradation. Their release can carry a high risk of environmental impacts, undermining the postulate that cleaning agents containing EPS are inherently harmless.

Economic Considerations

The financial consequences of using EPS as a cleaning agent and packaging material are real, especially on the scale-up of production and environmental effects. The capital-related aspect of upscaling EPS manufacture is a key financial concern due to the strain that expenses linked to the procurement of large machines, facility extension, and engaging qualified staff would place on financial resources (Ates, 2015). Losses incurred along the way when scaling up processes can result in increased operating expenses, which contribute negatively to profits.

Cost Control

To respond to these challenges, manufacturers are forced to take cost-controlling strategies (Elshorbagy *et al*., 2022; Verevkina *et al*., 2024). The application of lean manufacturing concepts has been effective in optimizing production activities by minimizing wastage and increasing efficiency. Simulation and estimation of prospective costs during the initial stages of scaling production enable them to discover opportunities for optimization (Ates, 2015).

Supply Chain Management

Disruptions to supply chains pose yet another serious threat to scaling up the production of EPS. Mitigating this threat involves building strong relationships with suppliers and multiple sourcing to ensure that there is no single dependence on a supplier. Active supply chain management techniques with aggressive quality control checks on incoming materials are essential in ensuring the efficiency of production (Ates, 2015; Alhazmi *et al*., 2022; Almohmmadi *et al*., 2022; Almuhanna *et al*., 2022). Supply chain analytics tools may help optimize inventory management and demand forecasting, thereby maintaining an uninterrupted flow of goods while incurring the lowest possible cost of shortages or overstocking (Ates, 2015).

Regulatory Compliance Costs

The highly controlled nature of pharmaceutical production, where EPS is commonly utilized, increases the complexity of scaling up production. Agencies such as the FDA and EMA enforce strict compliance with Good Manufacturing Practices (GMP), which can introduce higher compliance expenses throughout the scale-up process. Early consultation with regulatory agencies and the use of a Quality by Design (QbD) approach can reduce the complexity of compliance efforts and prevent possible economic costs of regulatory failure (Ates, 2015).

Technical Challenges in Production and Extraction

Limited Knowledge of Potential Species for EPS Production

One of the key challenges in EPS production is the lack of knowledge on the versatile species that can synthesize EPS. It is important to identify new microbial strains with the ability to produce EPS efficiently to drive production yields and broaden applications in numerous industries such as wastewater treatment and agriculture (Pan *et al*., 2016).

EPS Extraction Techniques

The recovery of EPS from microbial biofilms or cultures uses several physical and chemical procedures. Each of the extraction procedures has its advantages and disadvantages that can affect the quality and yield of EPS recovered. In most cases, chemical extraction procedures are more likely to recover more EPS than physical procedures; however, the chemicals used can interact with EPS and change their structure. The efficiency of extraction depends on various parameters, such as the actual technique employed, cell lysis in the case, and chemical residues within the extracts of EPS. Tough extraction may release intracellular materials into the EPS extract and make it more challenging to analyze the properties of EPS. The absence of a common extraction protocol makes it even more challenging to conduct research since the yield of extraction and physicochemical properties of EPS are highly dependent on the method used.

Mass Production Optimization

Another significant issue is the EPS manufacturing process's scalability. Existing procedures could no longer be profitable for use in business settings. To increase EPS yield while reducing costs, future research must focus on optimizing mass production techniques, such as fermentative methods and bioreactor design

(Pan *et al*., 2016). To overcome these technological challenges and make EPS a more feasible resource for a wide range of applications, new techniques for streamlining manufacturing and optimizing extraction process efficiency will be essential.

Future Prospects

The future of EPS as cleansing agents is promising, with ongoing research focused on enhancing their stability, bioactivity, and mechanical properties. The integration of EPS with inorganic materials, such as silver and gold nanomaterials, has been proposed to improve their performance in biomedical and environmental applications. Additionally, the development of nanomodified EPS composites offers innovative solutions for sustainable wastewater treatment and environmental remediation (Krishnaswamy *et al*., 2021; Show *et al*., 2024).

Conclusion

EPS represents a promising class of biopolymers that offer a wide range of applications in both environmental and industrial cleansing. These natural polymers possess unique properties that enable them to function effectively as biosorbents, flocculants, and protective barriers. This versatility makes EPS a sustainable alternative to traditional cleansing agents, which often have harmful environmental impacts. As ongoing research continues to uncover the full potential of EPS, we can anticipate their integration into innovative technologies that could significantly enhance the efficiency of bioremediation processes. This advancement is expected to not only improve the treatment of contaminated environments but also pave the way for new applications in various industries, ultimately contributing to a more sustainable and eco-friendly future.

Acknowledgments: The authors would like to thank Biotechnology Department and Centre of Excellence for Advanced Materials, Manufacturing, Processing and Characterization facility at Vignan's Foundation for Science, Technology & Research for necessary facilities.

Conflict of interest: None

Financial support: None

Ethics statement: None

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