



Review

Microbial Exopolysaccharides: Structure, Diversity, Applications, and Future Frontiers in Sustainable Functional Materials

Cláudia Mouro ^{1,2} , Ana P. Gomes ^{1,2} and Isabel C. Gouveia ^{1,2,*} ¹ FibEnTech Research Unit, Faculty of Engineering, University of Beira Interior, 6200-001 Covilhã, Portugal; anapaula@ubi.pt (A.P.G.)² AEROG-LAETA—Laboratório Associado em Energia, Transportes e Aeronáutica, Aerospace Sciences Department, Faculty of Engineering, University of Beira Interior, 6200-358 Covilhã, Portugal

* Correspondence: igouveia@ubi.pt; Tel.: +351-27-531-9825

Abstract: Exopolysaccharides (EPSs) are a diverse class of biopolymers synthesized by microorganisms under environmental stress conditions, such as pH, temperature, light intensity, and salinity. They offer biodegradable and environmentally friendly alternatives to synthetic polymers. Their structural versatility and functional properties make them unique in various industries, including food, pharmaceuticals, biomedicine, cosmetics, textiles, petroleum, and environmental remediation. In this way, among the well-known EPSs, homopolysaccharides like dextran, bacterial cellulose, curdlan, and levan, as well as heteropolysaccharides like xanthan gum, alginate, gellan, and kefiran, have found widespread applications in numerous fields. However, recent attention has focused on the potential role of extremophile bacteria in producing EPSs with novel and unusual protective and biological features under extreme conditions. Therefore, this review provides an overview of the functional properties and applications of the commonly employed EPSs. It emphasizes their importance in various industries and scientific endeavors while highlighting the raised interest in exploring EPSs with novel compositions, structures, and properties, including underexplored protective functionalities. Nevertheless, despite the potential benefits of EPSs, challenges persist. Hence, this review discusses these challenges, explores opportunities, and outlines future directions, focusing on their impact on developing innovative, sustainable, and functional materials.



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Keywords: biopolymers; exopolysaccharides; extremophiles; functional materials; sustainable materials; protective features

1. Introduction

Exopolysaccharides (EPSs) are fascinating biopolymers produced by various microorganisms, including bacteria, fungi, yeast, and microalgae [1–5]. In addition to these, natural polymers such as chitin and chitosan, found in the exoskeletons of arthropods or the cell walls of some fungi and yeast, also play significant roles in the field of natural polysaccharides due to their unique properties such as biocompatibility, biodegradability, and the ability to form fibers, films, and membranes. However, unlike EPSs, which microorganisms synthesize and secrete in response to a range of environmental challenges such as temperature variations, salinity, pH fluctuations, chemical agents, and radiation, chitin and chitosan are predominantly sourced from marine environments, contributing to biomedical, food, cosmetics, and pharmaceutical applications [6–9].

Natural polymers, including EPSs, play a crucial role in the survival and adaptation of microorganisms to adverse conditions [1–5,10–13]. In addition to their remarkable ability to thrive in hostile environments, EPSs offer several advantages over synthetic polymers. Their natural origin makes them biodegradable and environmentally friendly, unlike petroleum-based polymers that can persist in the environment for many years [4,5,14–32]. This attribute positions EPSs as sustainable and ecological alternatives in various industrial and scientific applications.

Furthermore, EPSs can adopt different forms, including capsular and slime, each with specific functions in cellular protection. Capsular forms create a protective layer around the cell. In contrast, slime EPSs can be secreted into the surrounding environment as a viscous or gelatinous substance, performing diverse functions such as adhesion, colonization, and protection against environmental stresses [1–3,5,33]. This versatility allows EPSs to be processed into various forms, such as biodegradable films, hydrogels, sponges, and nanocapsules for the controlled release of substances, among other applications [34].

Moreover, EPSs can be classified based on their carbohydrate structure into homopolysaccharides and heteropolysaccharides [4,14]. Their structural diversity makes them particularly attractive for a wide variety of applications, offering innovative and sustainable solutions in industries such as food production, agriculture, water treatment, cosmetics, pharmaceuticals, and biomedicine [2,3,5,35].

Among the various EPSs produced by extensively studied bacteria, Xanthan gum, produced by the bacterium *Xanthomonas campestris*, stands out in the food sector for its role in enhancing stability and viscosity by forming gels effectively even at low concentrations [5,36]. Furthermore, bacterial cellulose produced by *Komagataeibacter xylinus* has been used to manufacture biodegradable films for packaging and wound dressings owing to its excellent film-forming properties [36]. These are just two examples of EPSs that have garnered attention for their unique characteristics and specific functions, and many others have been widely explored due to their potential for applications in diverse fields (Figure 1) [2,5,16].

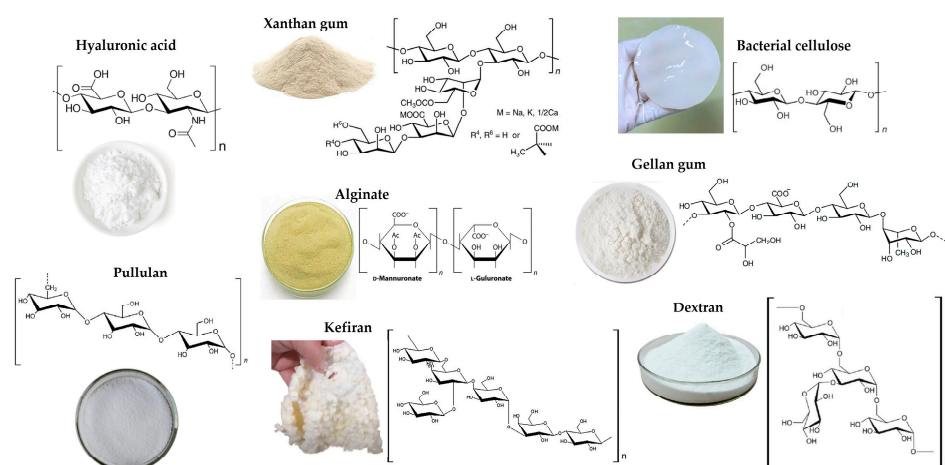


Figure 1. Chemical structures of the most representative exopolysaccharides (EPSs).

Recently, the number of these biopolymers has increased. Newly discovered bacteria capable of producing EPSs have been studied for their less explored functional properties, such as radiation protection, corrosion inhibition, and biological activities [37–39]. Among these new EPSs, those produced by extremophile bacteria stand out as promising sources of biopolymers with unique properties, offering new opportunities for innovative industrial applications [38–41].

Therefore, given the growing interest and emerging functionalities of EPSs, this review paper aims to provide a comprehensive overview of the diverse functions and applications of these polymers, showcasing recent advances in this field. The potential of EPSs as versatile and innovative materials is promising and inspiring, as they can drive significant advances in various industrial and scientific fields and contribute to sustainable and practical solutions. In addition, despite the limited practical applications of EPSs from extremophiles, this review paper emphasizes their unique properties and potential for innovative applications, highlighting the ongoing need for continued research and exploration in this promising field. Briefly, this review emphasizes the importance of EPSs in paving the way for a more sustainable and functional future.

2. Bibliometric Analysis

A bibliometric review focused on EPSs produced by extremophiles and their functional and sustainable properties was conducted as a promising approach to better understand the state of the art and emerging trends in this field.

2.1. Methodology

This bibliometric analysis used the following keyword combinations: “(Biopolymers OR Exopolysaccharides) AND Extremophiles” and “(Biopolymers OR Exopolysaccharides) AND Extremophiles AND (Functional materials OR Sustainable materials OR Protective features)”. These keywords were selected to capture a broad range of relevant studies, encompassing biopolymers in general and EPSs specifically, with a focus on extremophile sources.

2.2. Data Collection

Data were collected from major scientific databases, including Web of Science, Scopus, Science Direct, and Springer Link. These databases were selected for their extensive coverage of scientific literature across various disciplines. The search was limited to research and review articles published in peer-reviewed journals, ensuring the inclusion of high-quality and credible sources. The timeframe for the search was from 2020 to 2024, covering the most recent and relevant studies in the field.

2.3. Search Results and Analysis

The initial search yielded 25 documents from Web of Science, 29 from Scopus, 254 from ScienceDirect, and 108 from Springer Link for the keyword combination “(Biopolymers OR Exopolysaccharides) AND Extremophiles”. In turn, for the keyword combination “(Biopolymers OR Exopolysaccharides) AND Extremophiles AND (Functional materials OR Sustainable materials OR Protective features)”, the search yielded 3 documents from Web of Science, 0 from Scopus, 219 from Science Direct, and 47 from Springer Link. After applying the exclusion criteria, which focused on eliminating duplicate articles, papers addressing only peripheral or irrelevant aspects to the review scope, and those with an impact factor below 2, the final dataset comprised 93 documents, combining both keyword groups.

The final documents were organized into Table 1, which includes the article title, journal name, publication year, and impact factor. Further analysis was conducted based on several parameters, including trends over time, the most prolific journals, countries with significant contributions, and the co-occurrence of keywords.

The trend over time was examined to identify periods of increased research activity. Publications numbered 12 in 2020, 18 in 2021, 27 in 2022, 21 in 2023, and 15 in 2024 (Figure 2) indicate a general trend in research activity, with a peak in 2022 and sustained interest in EPSs from extremophiles.

In turn, the most prolific journals included the *International Journal of Biological Macromolecules* (13 publications) and *Bioresource Technology* (6 publications). Additionally, journals like *Biomass Conversion and Biorefinery* (3 publications), *Chemosphere* (3 publications), *Current Research in Microbial Sciences* (3 publications), and *Biotechnology Advances* (3 publications) highlighted the interdisciplinary nature of EPS research from extremophiles across biotechnology, biochemistry, environmental sciences, materials science, and microbiology (Figure 3). Moreover, it is important to note that Figure 3 showcases the more representative journals, while those with fewer publications (e.g., those receiving one publication) are not included.

Table 1. Comprehensive overview of selected research and review papers from bibliometric analysis.

No.	Article Title	Source Title	Publication Year	Impact Factor	Reference
1	Extremophiles as a green source of new exopolysaccharides with ecological importance and multifunctional applications	Polymer-Plastics Technology and Materials	2024	2.6	[40]
2	Exploring extremophiles from Bulgaria: Biodiversity, biopolymer synthesis, functional properties, applications	Polymers	2024	4.7	[35]
3	Extremophiles and their expanding biotechnological applications	Archives of Microbiology	2024	2.3	[10]
4	Exopolysaccharides from marine microbes: Source, structure and application	Marine Drugs	2022	4.9	[42]
5	Extremophilic exopolysaccharides: Biotechnologies and wastewater remediation	Frontiers in Microbiology	2021	4.0	[43]
6	Hydrating capabilities of the biopolymers produced by the marine thermophilic <i>Bacillus horneckiae</i> sBP3 as evaluated by aTR-FTIR spectroscopy	Materials	2022	3.1	[44]
7	Recent challenges and trends of polyhydroxyalkanoate production by extremophilic bacteria using renewable feedstocks	Polymers	2023	4.7	[17]
8	Biopolymer production by halotolerant bacteria isolated from <i>Caatinga</i> biome	Brazilian Journal of Microbiology	2021	2.1	[45]
9	Characterisation and bioactivities of an exopolysaccharide from an Antarctic bacterium <i>Shewanella frigidimarina</i> W32-2	Aquaculture	2021	3.9	[46]
10	Nature and bioprospecting of haloalkaliphilics: A review	World Journal of Microbiology and Biotechnology	2020	4.0	[47]
11	Arsenic adsorption and toxicity reduction of an exopolysaccharide produced by <i>Bacillus licheniformis</i> B3-15 of shallow hydrothermal vent origin	Journal of Marine Science and Engineering	2023	2.7	[48]
12	Exopolysaccharides production by cultivating a bacterial isolate from the hypersaline environment of Salar de Uyuni (Bolivia) in pretreatment liquids of steam-exploded quinoa stalks and enzymatic hydrolysates of Curupau sawdust	Fermentation-Basel	2021	3.3	[49]
13	Exopolysaccharide and biopolymer-derived films as tools for transdermal drug delivery	Journal of Controlled Release	2021	10.5	[41]
14	Characterization of Chilean hot spring-origin <i>Staphylococcus</i> sp. BSP3 produced exopolysaccharide as biological additive	Natural Products and Bioprospecting	2024	4.8	[50]
15	A review on production of polyhydroxyalkanoate (PHA) biopolyesters by thermophilic microbes using waste feedstocks	Bioresource Technology	2021	9.7	[51]
16	Bacillales: From taxonomy to biotechnological and industrial perspectives	Microorganisms	2022	4.1	[52]

Table 1. Cont.

No.	Article Title	Source Title	Publication Year	Impact Factor	Reference
17	Exopolysaccharide production using pinewood hydrolysate as a substrate for psychrotrophic bacterium isolated from Svalbard glacier soil	Biomass Conversion and Biorefinery	2023	3.5	[53]
18	<i>Halomonas alkaliantarctica</i> as a platform for poly(3-hydroxybutyrate-co-3-hydroxyvalerate) production from biodiesel-derived glycerol	Environmental Microbiology Reports	2024	3.6	[54]
19	UV and chemically induced <i>Halomonas smyrnensis</i> mutants for enhanced levan productivity	Journal of Biotechnology	2022	4.1	[55]
20	Cheese whey mother liquor as dairy waste with potential value for polyhydroxyalkanoate production by extremophilic <i>Paracoccus homiensis</i>	Sustainable Materials and Technologies	2022	8.6	[56]
21	Production of poly (3-hydroxybutyrate) and extracellular polymeric substances from glycerol by the acidophile <i>Acidiphilium cryptum</i>	Extremophiles	2023	2.6	[57]
22	Exopolysaccharide production by salt-tolerant bacteria: Recent advances, current challenges, and future prospects	International Journal of Biological Macromolecules	2024	7.7	[58]
23	Heavy metal tolerance, and metal biosorption by exopolysaccharides produced by bacterial strains isolated from marine hydrothermal vents	Chemosphere	2024	8.1	[59]
24	Polyhydroxyalkanoate biosynthesis and optimisation of thermophilic <i>Geobacillus stearothermophilus</i> strain K4E3_SPR_NPP	Extremophiles	2023	2.6	[60]
25	Trends in PHA production by microbially diverse and functionally distinct communities	Microbial Ecology	2023	3.3	[18]
26	Microbial polyhydroxyalkanoates (PHAs): A review on biosynthesis, properties, fermentation strategies and its prospective applications for sustainable future	Journal of Polymers and the Environment	2022	4.7	[19]
27	Technological advances in the production of polyhydroxyalkanoate biopolymers	Current Sustainable/Renewable Energy Reports	2020	3.1	[11]
28	Thermal properties of an exopolysaccharide produced by a marine thermotolerant <i>Bacillus licheniformis</i> by ATR-FTIR spectroscopy	International Journal of Biological Macromolecules	2020	7.7	[61]
29	Biological properties of exopolysaccharides produced by <i>Bacillus</i> spp.	Microbiological Research	2023	6.1	[62]
30	Potential functions and applications of diverse microbial exopolysaccharides in marine environments	Journal of Genetic Engineering and Biotechnology	2022	3.6	[63]

Table 1. Cont.

No.	Article Title	Source Title	Publication Year	Impact Factor	Reference
31	Synthetic biology of extremophiles: a new wave of biomanufacturing	Trends in Biotechnology	2023	14.3	[64]
32	Bacterial exopolysaccharides as emerging bioactive macromolecules: from fundamentals to applications	Research in Microbiology	2023	2.5	[65]
33	Polyhydroxyalkanoates from extremophiles: A review	Bioresource Technology	2021	9.7	[20]
34	Physicochemical characterization and emulsifying properties of a novel exopolysaccharide produced by haloarchaeon <i>Haloferax mucosum</i>	International Journal of Biological Macromolecules	2020	7.7	[66]
35	Production, characterisation, and application of exopolysaccharide extracted from a glacier bacterium <i>Mucilaginibacter</i> sp. ERM7:07	Process Biochemistry	2022	3.7	[67]
36	Microbial exopolysaccharides: Synthesis pathways, types and their commercial applications	International Journal of Biological Macromolecules	2020	7.7	[68]
37	Two new exopolysaccharides from a thermophilic bacterium <i>Geobacillus</i> sp. WSUCF1: Characterization and bioactivities	New Biotechnology	2021	4.5	[69]
38	Structural characterization and functional properties of novel exopolysaccharide from the extremely halotolerant <i>Halomonas elongata</i> S6	International Journal of Biological Macromolecules	2020	7.7	[70]
39	AepG is a glucuronosyltransferase involved in acidic exopolysaccharide synthesis and contributes to environmental adaptation of <i>Haloarcula hispanica</i>	Journal of Biological Chemistry	2023	4.0	[12]
40	Exopolysaccharide produced by potential probiotic <i>Enterococcus faecium</i> MS79: Characterization, bioactivities and rheological properties influenced by salt and pH	LWT	2020	6.0	[71]
41	Biopolymer production from biomass produced by Nordic microalgae grown in wastewater	Bioresource Technology	2023	9.7	[21]
42	Progresses and future prospects in biodegradation of marine biopolymers and emerging biopolymer-based materials for sustainable marine ecosystems	Green Chemistry	2022	9.3	[72]
43	A review of extracellular polysaccharides from extreme niches: An emerging natural source for the biotechnology. From the adverse to diverse!	International Journal of Biological Macromolecules	2021	7.7	[38]
44	Perspectives on the microorganism of extreme environments and their applications	Current Research in Microbial Sciences	2022	4.8	[73]

Table 1. Cont.

No.	Article Title	Source Title	Publication Year	Impact Factor	Reference
45	Current state of the art biotechnological strategies for conversion of watermelon wastes residues to biopolymers production: A review	Chemosphere	2022	8.1	[74]
46	Biopolymer poly-hydroxyalkanoate (PHA) production from apple industrial waste residues: A review	Chemosphere	2021	8.1	[75]
47	Comprehensive review on recent trends and perspectives of natural exo-polysaccharides: Pioneering nano-biotechnological tools	International Journal of Biological Macromolecules	2024	7.7	[76]
48	The metabolic pathways of polyhydroxyalkanoates and exopolysaccharides synthesized by <i>Haloferax mediterranei</i> in response to elevated salinity	Journal of Proteomics	2021	2.8	[22]
49	Metal(loid)-resistant bacterial consortia with antimycotic properties increase tolerance of <i>Chenopodium quinoa</i> Wild. to metal(loid) stress	Rhizosphere	2022	3.4	[77]
50	Polyhydroxyalkanoates synthesis by halophiles and thermophiles: towards sustainable production of microbial bioplastics	Biotechnology Advances	2022	12.1	[78]
51	Structural characteristics and immune-enhancing activity of an extracellular polysaccharide produced by marine <i>Halomonas</i> sp. 2E1	International Journal of Biological Macromolecules	2021	7.7	[79]
52	The radiophiles of <i>Deinococcaceae</i> family: Resourceful microbes for innovative biotechnological applications	Current Research in Microbial Sciences	2022	4.8	[80]
53	Archaea: current and potential biotechnological applications	Research in Microbiology	2023	2.5	[81]
54	The philosophy of extreme biomimetics	Sustainable Materials and Technologies	2022	8.6	[82]
55	Anti-allergic function of the cell wall (DeinoWall) from <i>Deinococcus radiodurans</i>	Molecular Immunology	2022	3.2	[83]
56	Untapped talents: insight into the ecological significance of methanotrophs and its prospects	Science of The Total Environment	2023	8.2	[84]
57	Genetic and process engineering for polyhydroxyalkanoate production from pre- and post-consumer food waste	Current Opinion in Biotechnology	2024	7.1	[23]
58	Application of microbial resources in biorefineries: Current trend and future prospects	Heliyon	2024	3.4	[85]
59	Cyanobacteria and microalgae in supporting human habitation on Mars	Biotechnology Advances	2022	12.1	[86]

Table 1. Cont.

No.	Article Title	Source Title	Publication Year	Impact Factor	Reference
60	Advancements in microbial production of polyhydroxyalkanoates (PHAs) from wastes for sustainable active food packaging: An eclectic review	Biocatalysis and Agricultural Biotechnology	2024	3.4	[24]
61	Recovery of value-added products from biowaste: A review	Bioresource Technology	2022	9.7	[87]
62	Engineering biosynthesis of polyhydroxyalkanoates (PHAs) for diversity and cost reduction	Metabolic Engineering	2020	6.8	[25]
63	Kinetics of two-step bioleaching of Ni and Co from iron rich-laterite using supernatant metabolites produced by <i>Salinivibrio kushneri</i> as halophilic bacterium	Hydrometallurgy	2020	4.8	[88]
64	Polyhydroxyalkanoates synthesis using acidogenic fermentative effluents	International Journal of Biological Macromolecules	2021	7.7	[26]
65	Waste to bioplastics: How close are we to sustainable polyhydroxyalkanoates production?	Waste Management	2021	7.1	[27]
66	Inulin from halophilic archaeon Haloarcula: Production, chemical characterization, biological, and technological properties	Carbohydrate Polymers	2023	10.7	[89]
67	Extraction, characterization, antioxidant activity and rheological behavior of a polysaccharide produced by the extremely salt tolerant <i>Bacillus subtilis</i> LR-1	LWT	2022	6.0	[90]
68	Polyhydroxyalkanoate bio-production and its rise as biomaterial of the future	Journal of Biotechnology	2022	4.1	[28]
69	Will the beneficial properties of plant-growth promoting bacteria be affected by waterlogging predicted in the wake of climate change: A model study	Applied Soil Ecology	2024	4.8	[91]
70	Novel fungal diversity: A new prospect for the commercial production of future anti-cancer compounds	Fungal Biology Reviews	2024	5.7	[92]
71	Polyhydroxyalkanoates (PHAs): From production to nanoarchitecture	International Journal of Biological Macromolecules	2020	7.7	[29]
72	Current advances and research prospects for agricultural and industrial uses of microbial strains available in world collections	Science of The Total Environment	2022	8.2	[93]

Table 1. Cont.

No.	Article Title	Source Title	Publication Year	Impact Factor	Reference
73	From waste management to circular economy: Leveraging thermophiles for sustainable growth and global resource optimization	Journal of Environmental Management	2024	8.0	[94]
74	Valorization of organic wastes using bioreactors for polyhydroxyalkanoate production: Recent advancement, sustainable approaches, challenges, and future perspectives	International Journal of Biological Macromolecules	2023	7.7	[30]
75	Marine microorganisms as an untapped source of bioactive compounds	Saudi Journal of Biological Sciences	2021	3.1	[95]
76	Hypersaline environments as natural sources of microbes with potential applications in biotechnology: The case of solar evaporation systems to produce salt in Alicante County (Spain).	Current Research in Microbial Sciences	2022	4.8	[96]
77	The production, recovery, and valorization of polyhydroxybutyrate (PHB) based on circular bioeconomy	Biotechnology Advances	2024	12.1	[31]
78	In vivo anti-inflammatory and antioxidant effects of microbial polysaccharides extracted from <i>Euganean</i> therapeutic muds	International Journal of Biological Macromolecules	2022	7.7	[97]
79	Biological and chemical characterization of new isolated halophilic microorganisms from saltern ponds of Trapani, Sicily	Algal Research	2021	4.6	[13]
80	Exploring the potential of Halomonas levan and its derivatives as active ingredients in cosmeceutical and skin regenerating formulations	International Journal of Biological Macromolecules	2023	7.7	[98]
81	The potential of cold-adapted microorganisms for biodegradation of bioplastics	Waste Management	2021	7.1	[99]
82	A novel higher polyhydroxybutyrate producer <i>Halomonas halmophila</i> 18H with unique cell factory attributes	Bioresource Technology	2023	9.7	[100]
83	The art of adapting to environments: The model system <i>Pseudoalteromonas</i>	Physics of Life Reviews	2021	13.7	[101]
84	Engineering microbial systems for the production and functionalization of biomaterials	Current Opinion in Microbiology	2022	5.9	[102]
85	Production of polyhydroxyalkanoates (PHAs) by a thermophilic strain of <i>Schlegelella</i> thermodepolymerans from xylose rich substrates	Bioresource Technology	2020	9.7	[103]
86	Biopolymers production from wastes and wastewaters by mixed microbial cultures: Strategies for microbial selection	Waste and Biomass Valorization	2020	2.6	[32]

Table 1. Cont.

No.	Article Title	Source Title	Publication Year	Impact Factor	Reference
87	Medium development and production of carotenoids and exopolysaccharides by the extremophile <i>Rhodothermus marinus</i> DSM16675 in glucose-based defined media	Microbial Cell Factories	2022	4.3	[104]
88	Melanin biopolymers from microbial world with future perspectives—a review	Archives of Microbiology	2022	2.3	[105]
89	Production and characterization of polyhydroxyalkanoates by <i>Halomonas alkaliantarctica</i> utilizing dairy waste as feedstock	Scientific Reports	2023	3.8	[106]
90	Biorefinery system for production of thermostable exopolysaccharide by a novel thermophile <i>Brevibacillus borstelensis</i> MK878423 and its study on impact of glucose utilization	Biomass Conversion and Biorefinery	2023	3.5	[107]
91	Characterization of water-soluble extracellular polysaccharide from <i>Aeribacillus pallidus</i> IM17	Indian Journal of Microbiology	2023	2.1	[108]
92	Current status and applications of genus <i>Geobacillus</i> in the production of industrially important products—a review	Folia Microbiologica	2022	2.4	[109]
93	Production of poly-gamma-glutamic acid (γ -PGA) from sucrose by an osmotolerant <i>Bacillus paralicheniformis</i> NCIM 5769 and genome-based predictive biosynthetic pathway	Biomass Conversion and Biorefinery	2023	3.5	[110]

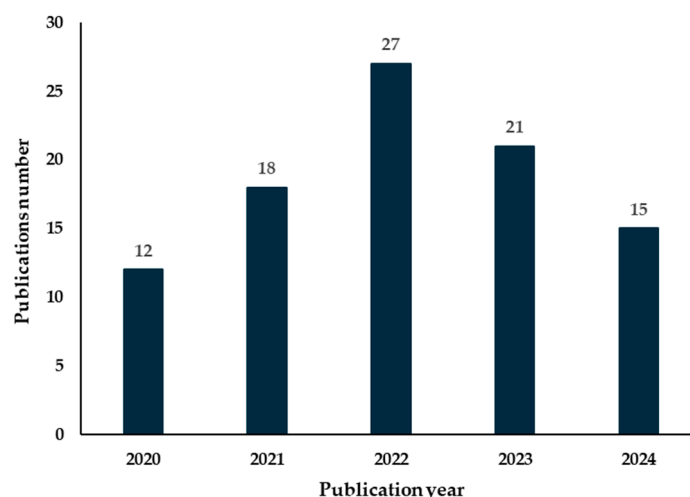


Figure 2. Bibliometric analysis on trends over time.

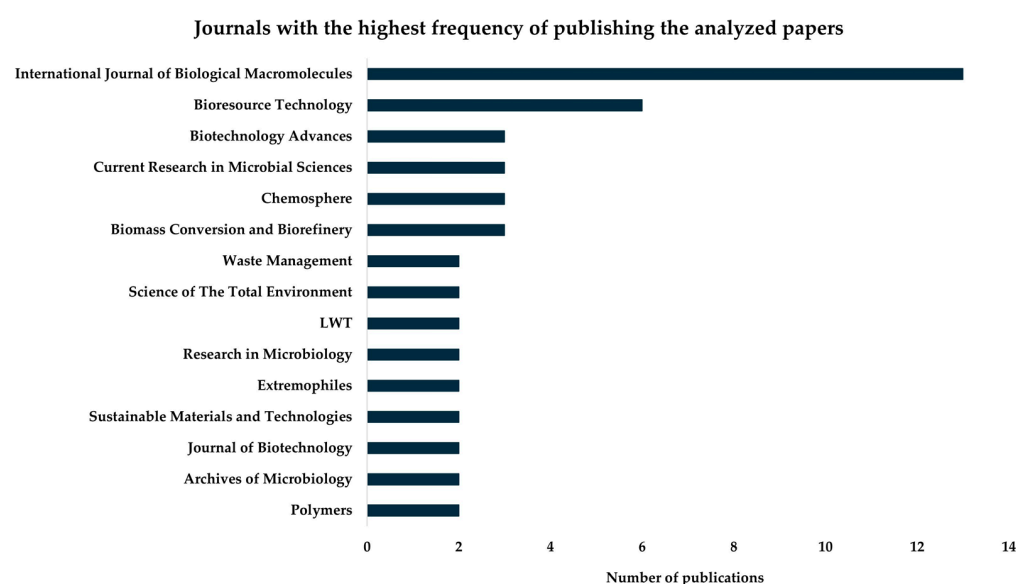


Figure 3. Graphic representation of the most prolific journals.

In addition, significant research contributions were notable from India, China, Italy, Poland, and the United States, underscoring their substantial output in the EPS research from extremophiles (Figure 4). These countries have emerged as leading contributors, driving advancements in the field through robust scientific infrastructure, research funding, and dedicated research initiatives in extremophile biology and biotechnology. Moreover, collaborative efforts across institutions and countries have further enriched the field, fostering diverse perspectives and expertise essential for expanding the applications of extremophile-derived EPSs in various domains.

Furthermore, keyword co-occurrence analysis using VOSviewer version 1.6.20 software identified key clusters and connections indicative of emerging trends in biopolymer research, particularly focusing on EPSs produced by extremophiles (Figure 5). This underexplored field highlights EPS production by organisms that survive in extreme conditions, such as halophiles and thermophiles, as evidenced by the strong connections between keywords like “Exopolysaccharides” and “Thermophile”. Moreover, the unique properties of these EPSs, including high stability and resistance to harsh environmental conditions, enable diverse applications such as bioremediation, environmental engineering, and novel material development. The map also highlights the integration of synthetic biology and metabolic engineering to optimize these processes, as indicated by the linkage between

"Synthetic biology" and "Metabolic engineering". This integration promises to expand the applications of EPSs, aligning with current trends in sustainability and the circular economy.

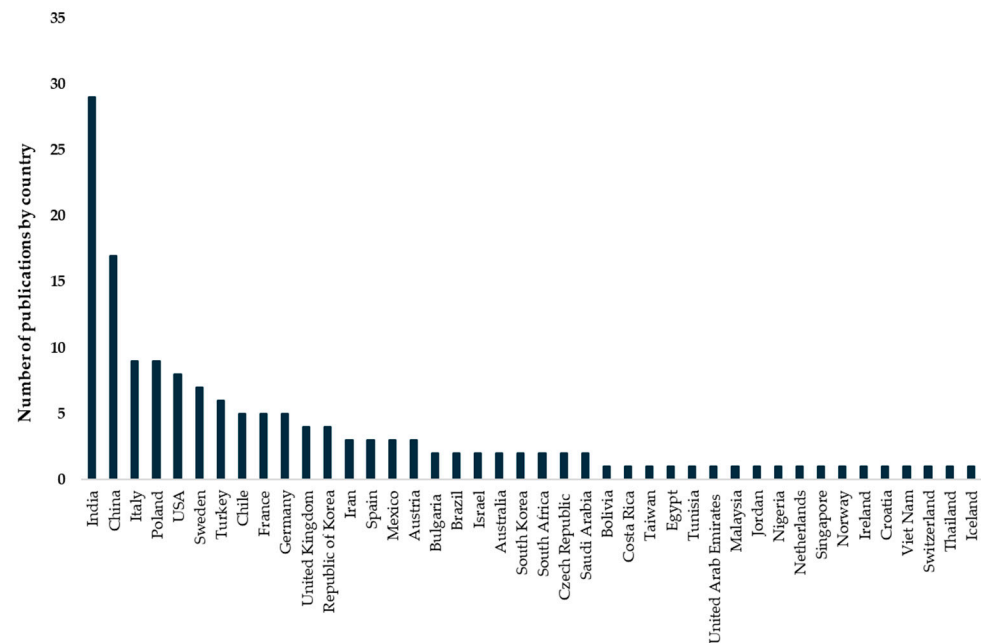


Figure 4. Graphical representation of the distribution of publications by country.

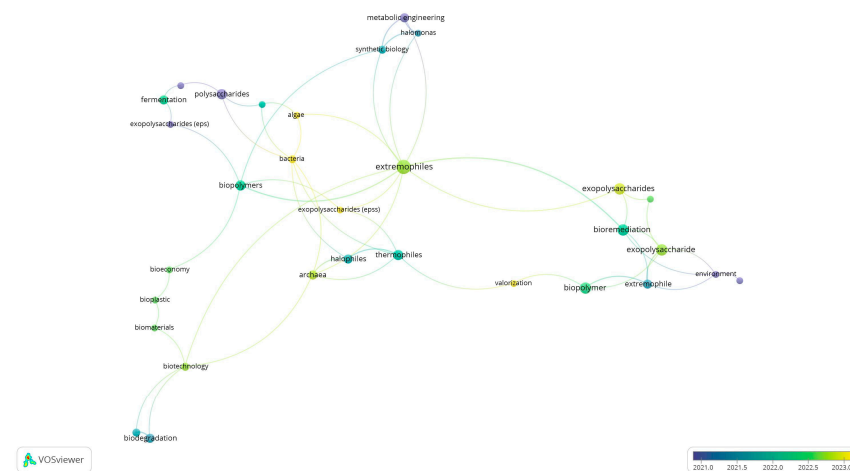


Figure 5. Bibliometric analysis using VOSviewer to represent co-occurring keywords.

EPSs represent a rapidly expanding sector within the biopolymers market. The global polysaccharides market was valued at USD 14.04 billion in 2021 and is projected to grow to USD 21.41 billion by 2030, indicating substantial growth in demand and applications [111]. Specifically, the global xanthan gum market, a prominent EPS example, was valued at around USD 1 billion in 2019 and is anticipated to increase to USD 1.5 billion by 2027. Additionally, the market for bacterial cellulose was evaluated at USD 250 million in 2017, with expectations to reach USD 680 million by the conclusion of 2025. The pullulan market is also set for growth, with projections to rise from USD 65 million in 2022 to USD 89 million by 2030. Moreover, the global dextran market achieved USD 203.9 million in 2021 and is forecasted to reach USD 284.5 million by 2028 [2].

Therefore, this review paper aims to enhance our understanding of the distinctive characteristics of EPSs, particularly those sourced from underexplored extremophiles, and investigate their promising applications across various sectors.

3. Exopolysaccharides (EPSs)

EPSs are large-molecular-weight carbohydrate biopolymers composed of sugar residues synthesized by microorganisms, including bacteria, fungi, yeasts, and microalgae, during their growth and metabolism. These secondary metabolites provide microenvironments that confer defense and protection under hostile conditions, play a key role in biofilm formation, contribute to bacterial pathogenicity, and maintain structural integrity and bacterial adhesion, among other functions [1–4,42,86,91].

EPSs are generally synthesized during the late exponential or stationary phase of microbial growth in response to various environmental stress conditions, including extreme temperature, salinity, unfavorable pH levels, osmotic stress, and exposure to radiation, chemical agents, antibiotics, heavy metals, and oxidants. However, EPS production can also occur as part of the microbial metabolic activities [1–5,34,73,105].

Moreover, after synthesis, EPSs can be found in two distinct forms: capsular polysaccharides, which adhere closely to the cell surface, creating a protective barrier around the cell; and free slime polysaccharides, which may be loosely adhered to the cell surface or secreted into the surrounding environment, creating a slimy or gel-like substance that assists various functions such as adhesion, colonization, and protection against environmental stresses [1–3,5,65].

In terms of their biochemical structure and composition, EPSs can be classified into homopolysaccharides or heteropolysaccharides, as summarized in Figure 6 [62]. Homopolymeric EPSs consist of repeating units of a single monosaccharide, commonly glucose and fructose, linked through glycosidic bonds. They are further divided into α -D-glucans (e.g., dextran, alternan, and reuteran), β -D-glucans (e.g., bacterial cellulose and curdlan), and fructans (e.g., levan and inulin). In turn, heteropolysaccharides have complex structures and are composed of repeating units of different monosaccharides, including glucose, fructose, galactose, mannose, rhamnose, fucose, arabinose, xylose, N-acetylglucosamine, and uronic acids, along with various non-carbohydrate groups. Examples of heteropolysaccharides include xanthan gum, alginate, hyaluronic acid, kefiran, gellan, and others [2,3,5,14].

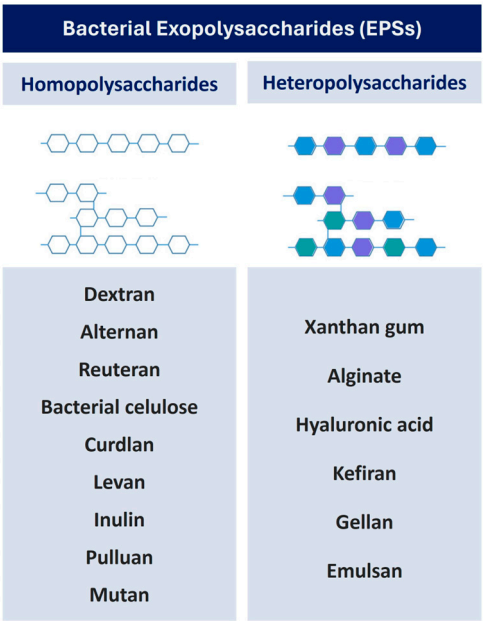


Figure 6. Illustration of the two types of bacterial EPSs: examples of homopolysaccharides and heteropolysaccharides.

The biosynthesis of EPSs is regulated by various factors, encompassing environmental conditions such as temperature, pressure, and light intensity, as well as the growth phase and nutrient availability, particularly the assimilation of a carbon substrate [2,14].

Nonetheless, the biosynthesis of EPSs in bacterial cells involves several well-established pathways, including the Wzx/Wzy-dependent pathway, the ATP-binding cassette (ABC) transporter-dependent pathway, synthase-dependent pathways, and extracellular biosynthesis utilizing a sucrose protein (Figure 7). Each pathway plays a distinct role in EPS synthesis and secretion, contributing to the diverse structures and functions observed across different EPS types. Typically, homopolysaccharides are synthesized via the synthase pathway or through extracellular biosynthesis facilitated by a single sucrose protein, while heteropolysaccharides employ the Wzx/Wzy-dependent and ABC transporter-dependent pathways [4,14,41,68,69].

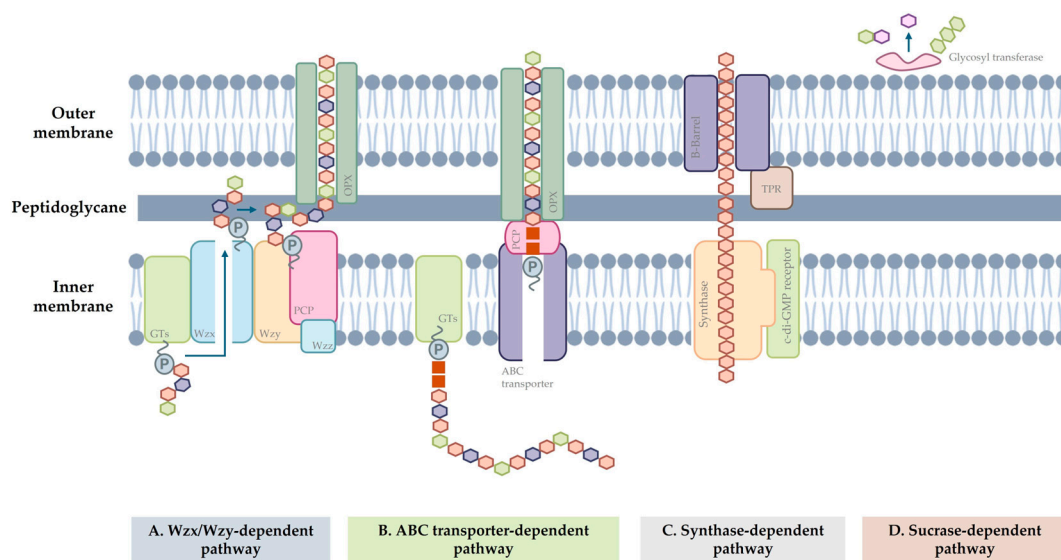


Figure 7. Microbial pathways involved in EPS synthesis: A—Wzx/Wzy-dependent pathway; B—ABC transporter-dependent pathway; C—Synthase-dependent pathway; D—Sucrose-dependent pathway.

Furthermore, most EPSs have a well-defined fermentation process critical for meeting the increasing global demand [5,16]. Moreover, microbial EPSs are rapidly produced in large amounts under controlled conditions, providing cost-effective alternatives to plant and algal polysaccharides, which exhibit limited seasonal availability, require significant time and cultivation resources, and are weather-dependent [5]. Additionally, EPS production costs can be reduced by using inexpensive alternative feedstocks sourced from agro-industrial waste. This approach can be complemented by optimizing fermentation processes, which involves adjusting cultivation conditions [2,14]. Moreover, the implementation of genetic and metabolic engineering techniques enables precise control over the yield and properties of EPSs [5,15].

Therefore, bacterial EPSs offer tremendous potential in numerous industrial sectors due to their unique structure and properties, which can be tailored for diverse applications. Abundant in natural sources, EPSs are non-toxic, biodegradable, biocompatible, exhibit excellent thermal stability, and possess suitable water retention capacity [4,5,14–16,34].

Furthermore, EPSs hold promise as alternatives to chemical drugs, being recognized as pharmaceutical and healthcare products, cosmeceutical, and nutraceutical, besides being applied in functional foods. Additionally, EPSs are used as biofertilizers and biocontrol agents in agriculture, contribute to oil recovery in petroleum industries, and assist in heavy metal removal. Their versatility extends to applications in drug delivery systems and scaffolds for tissue engineering. Moreover, EPSs have been effective in various sectors such as food, feed, packaging, chemicals, textiles, agriculture, and cosmetics. Their distinct structure and properties render them promising materials with potential applications in science, industry, medicine, and technology [3,5].

Hence, the following section of this review provides a concise overview of different bacterial EPSs used to produce functional materials, encompassing a wide range of applications. Table 2 outlines the principal features and key characteristics of the principal bacterial EPSs, including their main functional properties and applications. Additionally, particular emphasis is placed on synthesizing EPSs using alternative fermentation media derived from abundant and cost-effective sources such as lignocellulosic biomass and agro-food waste.

3.1. Homopolysaccharides EPSs

3.1.1. Dextran

Dextran is a well-known homopolysaccharide composed of glucose units interlinked with α -(1,6) glucoside linkages and α -(1,2), α -(1,3), and α -(1,4) branch linkages [36]. It is synthesized by lactic acid bacteria (LAB) belonging to the genera *Leuconostoc*, *Streptococcus*, *Weisella*, *Lactobacillus*, and *Pediococcus* using sucrose-rich media [36].

Dextran displays properties as a thickener, viscosifier, emulsifier, and stabilizer [36]. It is non-toxic, biodegradable, and biocompatible, and possesses anticancer, antibacterial, and antifungal capabilities, along with high aqueous solubility [15,112]. Moreover, despite its poor mechanical properties, dextran can be functionalized with various functional groups to encapsulate and/or conjugate different bioactive compounds [15]. These properties make dextran a promising candidate for drug delivery and coating material [15].

Dextran is used across various industries including food, cosmetics, and biomedical [3,15,112]. In cosmetics, it functions as a thickener and moisturizer [36]. In addition, dextran is valued for its ability to enhance skin health by smoothing, brightening, improving firmness, promoting radiance, and minimizing wrinkles [14]. In medicine, dextran serves as a drug carrier in tissue/cell cultures and is employed as a blood plasma volume expander, and in surgical sealants [14–16,112].

Dextran solutions lack color, odor, and taste and are chemically inert, making them compatible with various food ingredients [112]. Therefore, dextran is employed in confectionery and bakery products in the food industry to enhance softness and moisture retention, prevent crystallization, and improve viscosity, rheology, texture, and volume. Further, dextran acts as a stabilizer and thickening agent in ice creams and jams [2,14].

Due to its food-grade status, dextran has been proposed as a protective coating for perishable food. It is recommended for use in various biodegradable edible coatings and films, which exhibit excellent barrier properties and thereby extend food freshness [112].

Table 2. Well-known exopolysaccharides produced by bacteria and their corresponding functional properties and potential applications.

EPS	Producer Organisms	Substrates	Monomer Composition	Molecular Weight (Da)	Functional Properties	Applications	Refs.
Dextran	<i>Leuconostoc mesenteroides</i> , <i>Leuconostoc dextranicum</i> , <i>Lactobacillus hilgardii</i> , <i>Streptococcus mutans</i>	Sucrose	Glucose	3.0×10^3 – 3.0×10^6	Thickening, viscosifying, emulsifying, and stabilizing properties; non-toxic, biodegradable, and biocompatible; anticancer, antibacterial, and antifungal capabilities; high aqueous solubility.	It is used to improve the softness, moisture retention, and texture of bakery products and confectionery, prevents crystallization, and stabilizes and thickens ice creams and jams. It has potential for biodegradable edible coatings and films for perishable food. It is used as a carrier for drug delivery, blood plasma volume expander, and surgical sealant. It enhances skin health and appearance by acting as moisturizers and thickeners in cosmetics. It is also used as a chromatographic media.	[2,3,14–16,36,112]
Alternan	<i>Leuconostoc mesenteroides</i> , <i>Leuconostoc citreum</i> , and <i>Streptococcus salivarius</i>	Sucrose	Glucose	10^6 – 10^7	Solubility in water, low viscosity, and strong resistance to enzymatic hydrolysis.	It is used as a prebiotic ingredient, low caloric bulking agent, and binder for food. Lipid-substitute texturizer in cosmetic preparations. It also promotes the growth, migration, and differentiation of human mesenchymal stem cells (MSCs). It enhances the strength of dry paper when added during the papermaking process. It can be also used as inks and glues.	[4,113–116]
Reuteran	<i>Limosilactobacillus reuteri</i>	Sucrose	Glucose	2.8×10^7	Water-soluble and non-Newtonian behavior in aqueous solution.	It is used as a dietary fiber and prebiotic additive to enhance satiety and gut health. It enhances the quality and texture of wheat bread and gluten-free sourdough. It induces or enhances satiety in humans and animals.	[113,116,117]

Table 2. Cont.

EPS	Producer Organisms	Substrates	Monomer Composition	Molecular Weight (Da)	Functional Properties	Applications	Refs.
Bacterial Cellulose	<i>Gluconacetobacter</i> , <i>Agrobacterium</i> , <i>Rhizobium</i> , <i>Salmonella</i> , and <i>Sarcina</i>	Sucrose, fructose, molasses, arabitol, and mannitol	Glucose	3.0×10^5 – 2.0×10^6	High purity, surface area, yield, polymerization degree, crystallinity, tensile strength, water-holding capacity, lightweight nature, transparency, flexibility, biocompatibility, biodegradability, renewability, non-toxicity, and non-immunogenicity.	It is used as a promising biomaterial for wound dressings, tissue engineering, and drug delivery. It is applied in artificial blood vessels and implants. It is used in cosmeceutical face masks to act as a carrier for bioactive agents and enhance skin hydration. It acts as an emulsion stabilizer in cosmetic formulations. It is used as a thickener, gelling agent, and a natural non-digestible fiber. It is used in food packaging. It is used for pollutant detection and waste decomposition. It is also applied in nanoelectronics, textile fashion, biocatalytic technologies, and paper production.	[5,16,36,113,118–120]
Curdlan	<i>Agrobacterium</i> sp., <i>Rhizobium</i> sp., <i>Bacillus</i> sp., and <i>Cellulomonas</i> sp.	Glucose and sucrose	Glucose	5.0×10^4 – 2.0×10^6	Soluble in alkaline solutions but insoluble in water (can be solubilized in water with salt), has antitumoral properties immunomodulatory capability, thermostability, thermogelation properties, water-holding capacity, and potential antioxidant capability.	It is used for drug encapsulation, modulation of immune responses, and scaffold or wound dressing production. It promotes mesenchymal cell adhesion and enhances bone growth. It is used as drug delivery vehicles for sustained release. It is used as a thickener, stabilizer, texturizer, binder, and dietary fiber. It enhances the creaminess, stability, and texture of food products. It is used as an edible and biodegradable food packaging film. It is also used to remove heavy metals when combined with activated carbon adsorbents.	[3,4,14,15,36,113,121,122]

Table 2. Cont.

EPS	Producer Organisms	Substrates	Monomer Composition	Molecular Weight (Da)	Functional Properties	Applications	Refs.
Levan	<i>Acetobacter, Bacillus, Brenneria, Geobacillus, Halomonas, Lactobacillus, Zymomonas, and Saccharomyces</i>	Sucrose	Fructose	10 ⁴ –10 ⁸	Soluble in both water and oil, while remaining insoluble in most organic solvents; Antitumor, antioxidant, antibacterial, anti-inflammatory, anti-hyperlipidemic, radioprotective, immunomodulatory, and prebiotic activities; heat stability, high adhesive strength, and film-forming ability.	It serves as a thickener, emulsifier, stabilizer, gelling agent, film-former, encapsulant, cryoprotector, osmoregulator, and flavor carrier. It is used as a prebiotic food supplement and for food packaging. It is used as a plasma volume expander, agent for combating obesity, antitumor agent, and hyperglycemic inhibitor. It is used as an adhesive for wood bonding and a biological binder for producing wood biocomposite materials. It is suitable for cosmetic formulations. It is also used as adsorbent for heavy metals.	[3,5,15,36,113,123]
Inulin	<i>Streptococcus mutans, Limosilactobacillus reuteri, Leuconostoc citreum, and Lactobacillus johnsonii</i>	Fructose and glucose	Fructose	5.0 × 10 ² –1.3 × 10 ⁴	Soluble in water; enhances water viscosity; enhances calcium absorption; Inhibits biofilm formation; antioxidant activity.	It is used to reduce food calories and replace fats and sugars. It has a prebiotic function. It acts as a stabilizing agent and cryoprotectant foodstuffs. It is used to reduce cancer risk (especially colon cancer). It is used as a carrier for drug delivery in colon diseases. It reduces irritable bowel disease risk and provides constipation relief.	[4,89,113,124,125]

Table 2. Cont.

EPS	Producer Organisms	Substrates	Monomer Composition	Molecular Weight (Da)	Functional Properties	Applications	Refs.
Pullulan	<i>Aureobasidium pullulans</i> , <i>Cytaria</i> spp., <i>Teloschistes flavicans</i> , <i>Rhodotorula bacarum</i> , and <i>Cryphonectria parasitica</i>	Glucose, sucrose, mannose, galactose, and fructose	Glucose	5.0×10^3 – 9.0×10^6	Highly soluble in water; thermal stable; adhesive properties; robust mechanical strength; resistance to pH changes; non-mutagenic, non-carcinogenic, and non-immunogenic; ability to form strong, flexible films and fibers; biodegradable; biocompatible; odorless and tasteless; act as a thickening and stabilizing; prebiotic and antioxidant properties.	It is used as a carrier for gene and drug delivery, and in tissue engineering, biomedical imaging, plasma expanders, nasal vaccine adjuvants, vaccine formulations, skincare products and cosmetic formulations. It is used as a dietary fiber in low-calorie foods and in packaging films, edible films, food coating, carrier for flavors and antimicrobial compounds, viscosity stabilizer and thickening agent, and prebiotics. It is used in waste remediation, analytical techniques, and energy and electronics sectors.	[3,15,36,113,126–132]
Mutan	<i>Streptococcus mutans</i> and <i>Streptococcus sobrinus</i>	Sucrose	Glucose	5.65×10^3	Sticky, colorless, and water-insoluble.	It is used to inhibit dental plaque and dental caries. It is also used to adsorb heavy metals.	[4,118,133–135]
Xanthan gum	<i>Xanthomonas campestris</i>	Glucose and sucrose	Glucose, glucuronic acid, and pyruvic acid	2.0×10^6 – 2.0×10^7	Soluble in water; high viscosity; non-toxic; resistant to environmental factors; pseudoplastic; biodegradable; cost-effective; antioxidant effects; antimicrobial and antitumoral properties; viscosifying and stabilizing properties.	It is used as a carrier and scaffold for drug delivery. It is used in tissue engineering, in wound dressings, in intra-articular injections, and as an adjuvant in the immune system. It is used in the production of cosmetics, detergents, insecticides, and eco-friendly absorbents. It acts as a thickener, stabilizer, emulsifier, foam stabilizing agent, and crystal formation inhibitor in various food products. It is also used in oil recovery and viscosity control in drilling, and in 3D printing technology.	[3,5,15,16,36,113,136]

Table 2. Cont.

EPS	Producer Organisms	Substrates	Monomer Composition	Molecular Weight (Da)	Functional Properties	Applications	Refs.
Alginate	<i>Pseudomonas aeruginosa</i> and <i>Azotobacter vinelandii</i>	Glucose and sucrose	Guluronic acid and mannuronic acid	0.5×10^6 – 1.5×10^6	Soluble in water; biocompatible and biodegradable; ability to form hydrogels; water-holding capacity; viscosity regulator and stabilizing properties.	It is used for encapsulating drugs, growth factors, and cells. It is used to produce scaffolds for tissue engineering. It is used as fillers and carriers for osteoinductive factors in bone engineering. It is used as a thickening agent, gelling agent, and excipient in skin and cosmetic formulations. It serves as a regulator of viscosity, stabilizer, and material for packaging.	[4,14–16,113]
Hyaluronic Acid	<i>Streptococcus equi</i> , <i>Streptococcus equisimilis</i> , <i>Streptococcus pyogenes</i> , and <i>Streptococcus thermophilus</i>	Glucose and sucrose	Glucuronic acid and N-acetylglucosamine	1.0×10^6 – 2.0×10^6	High water retention capacity; biocompatible, biodegradable, and non-immunogenic; moisture-absorption properties; viscoelastic; enhance cell adhesion and proliferation; ability to form a non-Newtonian solutions with gel-like properties; anti-inflammatory properties; Compatible with biological systems; Angiogenesis modulation.	It is used as a moisturizing agent in skincare and cosmetic products. It is used in the formulation of pharmaceuticals and artificial tear solutions. It is used in cancer treatment. It triggers angiogenesis, wound healing, and cell motility. It is used in tissue engineering scaffolds. It is used in the treatment of osteoarthritis. It is used as a replacement for natural eye fluid during ophthalmic surgeries and joint lubricant to replace synovial fluid. It is used to prevent adhesions in abdominal surgeries. It is used as a surface coating in medical applications. It is used as a food ingredient.	[3,15,16,36,137,138]

Table 2. Cont.

EPS	Producer Organisms	Substrates	Monomer Composition	Molecular Weight (Da)	Functional Properties	Applications	Refs.
Kefiran	<i>Lactobacillus kefir</i> , <i>Lactobacillus parakefir</i> , <i>Lactobacillus kefiranofaciens</i> , <i>Lactobacillus kefirgranum</i> , and <i>Lactobacillus delbrueckii</i> subsp. <i>bulgaricus</i>	Lactose, molasses, and whey lactose	Glucose and galactose	5.0×10^4 – 1.5×10^7	Water soluble; semi-crystalline nature; resistance to hydrolysis; gels and films formation ability; water vapor barrier properties; antibacterial and antioxidant properties; antitumor and mucosal adjuvant properties; biodegradable and biocompatible.	It is used for tissue engineering, controlled drug and probiotic delivery, and wound dressings. It is also used as edible biofilms and biodegradable food packaging. It is used for food stabilization and in thickening agents in fermented dairy products.	[2,4,16,113,139,140]
Gellan	<i>Sphingomonas paucimobilis</i>	Fructose, sucrose, glucose, and lactose	Glucose and rhamnose	5.0×10^3 – 2.0×10^6	Insoluble in cold water; resistance to enzymatic degradation; thermo-reversible gel formation; reduced susceptibility to pH changes; low mechanical resistance and high polyelectrolyte content.	It is used as a stabilizer, binder, thickener, and gelling agent in food products, and enhances texture and flavor release in desserts, jams, and ice creams. It acts as a carrier for vitamin C and encapsulates heat-sensitive ingredients. It is used for controlled drug release and tablet disintegration. It supports cell adhesion, proliferation, and differentiation. It is used in paper coatings, and serves as a water flocculent. It is helpful in the bioremediation of polluted soils and aquifers.	[14–16,36,141]
Emulsan	<i>Acinetobacter venetianus</i> and <i>Acinetobacter calcoaceticus</i>	Sucrose	Glucose, α - and β - hydroxydodecanoic acid	1.0×10^6	Amphiphilic properties; chemical and biological versatility; bioemulsifying properties.	It is used as stable hydrocarbon-in-water emulsions for industrial and environmental purposes. It is used for drug delivery. It is used as a bioemulsifier in food processing. It is also used in personal care products like cleansing creams, lotions, shampoo, soap, and toothpaste. It acts as a vaccine adjuvant.	[14,36,142–146]

However, the versatility of dextran extends beyond its known applications. Researchers have actively explored cost-effective and renewable carbon sources for dextran production to enhance industry scalability and sustainability. Promising avenues involve sugarcane molasses (SCMs), a low-cost feedstock sourced from agricultural byproducts [147]. Moreover, attention has also turned towards unconventional substrates such as brewers' spent grain (BSG), a prevalent byproduct of the beer brewing industry, offering potential routes for dextran biosynthesis [148]. Similarly, efforts are underway to optimize conditions for dextran production from pineapple waste and *Saccharum officinarum* juice (SOJ), which represent additional renewable carbon sources [149,150].

3.1.2. Alternan

Alternan is a homopolysaccharide classified under α -D-glucans, characterized by alternating (α -1,6) and (α -1,3) linkages with a low degree of branching, primarily produced by *Leuconostoc mesenteroides*, *Leuconostoc citreum*, and *Streptococcus salivarius* [4,114,151]. Unlike dextran, alternan demonstrates distinct physicochemical properties, including higher water solubility and lower viscosity. Moreover, alternan shows exceptional resistance to hydrolysis by both mammalian and microbial enzymes [114–116].

In the food industry, alternan is a functional food ingredient, functioning as a prebiotic and texturizing agent and offering a low-calorie alternative to fat or oil components in various foods [115,116]. Alternan-based products or formulations, such as lipid-substitute texturizers for cosmetic preparations like creams and ointments, have been patented. In papermaking, alternan enhances the dry strength of paper when used as a wet-end additive [116].

Moreover, alternan is commonly employed as a thickening agent, often in combination with other thickeners [115]. Further, it has also shown potential applications in inks and glues [115]. Alternan has been demonstrated to promote human mesenchymal stem cells' growth, migration, and differentiation, suggesting promising medical applications in tissue regeneration and wound healing [115].

3.1.3. Reuteran

Reuteran is a water-soluble α -glucan synthesized by the enzyme reuteransucrase from *Limosilactobacillus reuteri*. When dissolved in water, reuteran contains significant amounts of α -(1,4)-glucosidic bonds and exhibits milky-white opalescence and non-Newtonian properties [113,116,151,152].

Different studies have examined reuteran for its potential health-promoting properties as a food additive. Incorporating reuteran in baking applications improves bread quality and texture. Furthermore, highly branched reuteran can serve as a dietary fiber, contributing to the induction and enhancement of satiety in humans and animals [116].

It improves the quality of gluten-free sourdough and sorghum bread, resulting in a softer texture, longer shelf life, and prebiotic benefits [113].

3.1.4. Bacterial Cellulose

Bacterial cellulose is an EPS produced by various bacterial species. *Gluconacetobacter*, along with *Agrobacterium*, *Rhizobium*, *Salmonella*, and *Sarcina*, includes species notably recognized for their cellulose production capability. Among these, *Gluconacetobacter* species are particularly renowned for their efficiency in cellulose production [36].

Although its chemical composition is similar to that of plant cellulose, bacterial cellulose exhibits unique features such as high purity, large surface area, high yield, high degree of polymerization, crystallinity, tensile strength, water-holding capacity, lightweight nature, transparency, flexibility, biocompatibility, biodegradability, renewability, and is known for its non-toxic and non-immunogenic properties. Moreover, one significant advantage is the absence of hemicelluloses, lignins, and pectins, which simplifies the extraction process [5,36,113].

These properties make bacterial cellulose a versatile biopolymer suitable for various applications in food, cosmetics, biomedical, and engineering fields [5]. In biomedicine, it has been used effectively in wound dressings, tissue engineering, and controlled drug release systems [5,119]. Additionally, it holds promise for creating artificial blood vessels, vascular grafts, and implants. In cosmeceutical applications, bacterial cellulose has been used in face masks for delivering bioactive agents and providing skin hydration. Furthermore, bacterial cellulose has also been used as an emulsion stabilizer [5,118,119].

In the food industry, bacterial cellulose is valued for its high purity and adaptable texture and shapes, ranging from spheres, particles, and filaments to films, multi-shaped pulps, and whiskers. It has been widely used as a thickener and gelling agent to improve water retention in surimi, strengthen tofu gels, and replace fat in meatballs. Additionally, it has also been used to stabilize emulsions and foams in ice cream and immobilize probiotic bacteria. As a natural, non-digestible fiber, bacterial cellulose helps reduce food calories and improve health, making it a beneficial component in dietary fiber products. Moreover, bacterial cellulose has contributed to innovative and sustainable food packaging solutions that enhance product preservation [5,36,113,119].

In the environmental sector, bacterial cellulose serves as a matrix for immobilizing catalysts and enzymes, aiding in pollutant detection and waste decomposition, including heavy metals, fluorine, organic pollutants like dyes and pharmaceutical compounds, and petroleum products. In nanoelectronics, it is used in sensors, optoelectronic devices, flexible displays, energy storage systems, and membranes for acoustic applications. The textile industry has also investigated its use in fashion, as demonstrated in studies performed by Suzan Lee. Furthermore, bacterial cellulose functions as a carrier for microorganisms or enzymes in biocatalytic technologies and as a binder in high-quality paper production [5,119].

However, despite all these advancements, bacterial cellulose biosynthesis presents several limitations that hinder its widespread application and efficiency. These limitations include production costs, complexity of growth medium formulation, and scalability issues.

Interestingly, the carbon source influences bacterial cellulose's water-holding capacity, mechanical properties, and molecular weight without impacting its chemical structure [16]. Concerning this, researchers have explored alternative substrates for cellulose production to address the limitations of the commonly used Hestrin–Schramm (HS) medium, which contains expensive constituents such as glucose, yeast extract, peptone, citric acid, and disodium phosphate. These alternatives encompass agro-wastes, pulp mill and lignocellulosic wastes, residues from the biodiesel industry, and wastewater from acetone–butanol–ethanol fermentation [5,153–157].

Moreover, the cultivation technique of bacterial cellulose also plays a vital role in determining its production yield and physical characteristics. Under static conditions, bacteria produce cellulose as a film on the medium's surface, while agitated conditions result in cellulose forming agglomerates of various shapes. Recent studies comparing static and agitated conditions have generally observed higher bacterial cellulose yields in static cultures, although some reports suggest higher yields in agitated cultures [5].

3.1.5. Curdlan

Curdlan is a neutral and acidic linear glucan composed of β -(1,3)-glycosidic bonds, with a molecular weight ranging from 5×10^4 to 2×10^6 Da. Moreover, it is produced as a secondary metabolite by *Agrobacterium* sp., *Rhizobium* sp., *Bacillus* sp., and *Cellulomonas* sp. under nitrogen-limiting conditions, using glucose or sucrose as a carbon source [36,113]. Curdlan is soluble in alkaline solutions but remains insoluble in water (although it can be solubilized in water with salt). It is colorless, odorless, tasteless, and indigestible [113]. Moreover, curdlan displays antitumoral properties, enhances cytokine production, and reduces inflammation [15]. Additionally, it aids in drug release due to its ability to form gels in response to temperature changes.

These unique properties and versatile characteristics make curdlan an excellent choice for various applications across various fields and industries. In the medical industry, it has

shown particular promise for drug encapsulation, modulation of immune responses, and as a component in fabricating composite scaffolds or wound dressings that enhance mechanical and biological properties [15,113]. Curdlan supports mesenchymal cell adhesion and promotes bone growth [3]. Additionally, curdlan and its derivatives have also been effective in drug delivery systems to sustain drug release. Furthermore, curdlan efficiently regulates innate and adaptive immune responses by interacting with immune receptors such as Dectin-1 and cells, including macrophages, neutrophils, monocytes, dendritic, and natural killer (NK) cells [121].

Curdlan has also proven valuable as a versatile additive with multiple functions in the food industry. Recognized by the Food and Drug Administration (FDA) as a stabilizer and texturizer, it is used as a binder and dietary fiber in its gel form. Its thermostable properties make it an ideal additive for improving the creaminess, stability, and viscoelasticity of various food products [36]. Additionally, curdlan is commonly employed as a thickener, stabilizer, and texturizer in food processing, contributing to enhanced yogurt stability and improved texture of noodles, sauces, frozen foods, and packaged meats, among other applications [14,121]. Moreover, curdlan has shown potential as an edible and biodegradable film for food packaging [113]. Additionally, recent research has highlighted curdlan's thermostability and excellent water-holding capacity from *Rhizobium radiobacter*, suggesting its potential as an antioxidant and prebiotic agent, though further studies are needed to fully explore its biological potential [122].

Finally, recent studies have demonstrated that curdlan, when combined with activated carbon adsorbents, can remove heavy metals, expanding its potential applications in environmental remediation and water purification processes [121]. However, despite the high demand for curdlan, its industrial use is limited due to the costly conventional sugar feedstocks. In response, researchers have proposed *Musa sapientum* peels hydrolysate (MPH) and dried orange peels as sustainable media for curdlan production [158,159]. These agricultural byproducts have shown promise in enhancing curdlan yield. Moreover, cassava starch waste hydrolysate, wheat bran, and various plant biomass hydrolysates are promising, cost-effective, and sustainable feedstocks for improving curdlan's industrial applications [160].

3.1.6. Levan

Levan, a fructose-based homopolysaccharide with a molecular weight ranging from 10^4 to 10^8 Da is synthesized by various microorganisms such as *Acetobacter*, *Bacillus*, *Brenneria*, *Geobacillus*, *Halomonas*, *Lactobacillus*, *Zymomonas*, and *Saccharomyces*, using levansucrases. It is characterized by its neutral composition and the presence of β -2,6-glycoside bonds in the backbone and β -2,1 bonds in its branches [5,15,36,98,113].

Levan is a versatile polymer that is soluble in water and oil but insoluble in most organic solvents. Despite its low intrinsic viscosity and resistance to dissolution or swelling in water at room temperature, it exhibits heat stability, high adhesive strength, and film-forming properties [5,36,113].

Recognized as one of the most promising biocompatible and non-toxic microbial EPSs, levan presents a wide range of beneficial functional properties, including antitumor, antioxidant, antibacterial, anti-inflammatory, anti-hyperlipidemic, radioprotector, immunomodulatory, and prebiotic activities [3,5]. Due to these attributes, levan is considered industrially significant, finding extensive applications in the food, biomedicine, cosmetic, and pharmaceutical sectors [5,36]. Its versatility makes it highly promising for biomedical applications such as plasma volume expanders, anti-obesity therapy, antitumor treatments, and hyperglycemia management [113]. Levan has demonstrated efficacy against various human conditions, including cancer, heart disease, and diabetes, with specific antitumor properties observed against neuroblastoma and osteosarcoma cells, attributed to its recognition ability by GLUT5 [5,15].

Furthermore, levan's amphiphilic properties make it ideal for nanoparticle formation, enhancing its potential as an effective drug carrier. Additionally, due to its immune

system-modulating capabilities, levan is widely used in pharmaceuticals as a carrier and drug-coating material [3,5]. Moreover, levan contributes to the formulation of safe and effective body washes in cosmetics [5].

In the food industry, levan serves various roles as a thickener, emulsifier, stabilizer, gelling agent, film-forming agent, encapsulating agent, cryoprotector, osmoregulator, and flavor carrier. Its application in confectionery is notable, as it acts as a viscosifier and stabilizer [3,36]. Moreover, levan functions as a prebiotic food supplement [5,113].

In contrast, despite the inherent brittleness of pure levan films, biodegradable levan-based films offer practical oxygen barriers suitable for food packaging [5,36,113]. In addition to its film-forming ability, levan exhibits high adsorption properties, making it a sound material for capturing heavy metals in the treatment of industrial wastewater. Its adhesive properties also qualify it for wood bonding, potentially serving as a biological binder for wood biocomposite materials [5].

Therefore, levan holds promise for developing biocomposites due to its versatile properties and environmentally friendly nature [5]. However, despite its many applications, the commercial availability of levan remains limited due to the high production costs associated with traditional methods [161]. In response, researchers have explored genetic manipulation techniques to develop new strains and investigated the use of inexpensive agro-industrial byproducts as substrates for levan production [161]. As an alternative approach, a recent study employed a fermentation medium composed of sugarcane juice (SJ) and chicken feather peptone (CFP) for microbial synthesis of levan, aiming to address the economic viability challenge and provide a cost-effective solution for levan biosynthesis [162].

3.1.7. Inulin

Inulin-type EPSs, known as fructooligosaccharides, are synthesized by *Streptococcus mutans*, *Limosilactobacillus reuteri*, *Leuconostoc citreum*, and *Lactobacillus johnsonii* [4,89,113]. Inulin exhibits various functional properties, including its ability to increase water viscosity [113]. Moreover, inulin presents several functional benefits, such as enhancing calcium absorption, inhibiting biofilm formation through specific antimicrobial molecules, and demonstrating antioxidant activity [124].

In addition, inulin-type EPSs find diverse applications in the food industry and show potential therapeutic benefits [113,124]. In the food industry, inulin fulfills multiple functions. It reduces food calories and blood triglycerides, acts as a fat and sugar replacer, and is a water-soluble fiber fermented by intestinal bacteria, producing short-chain fatty acids [113]. Additionally, it is commonly used as a prebiotic in human and animal food products and has recently received FDA approval to enhance nutritional values. Moreover, inulin is a stabilizing agent and cryoprotectant in foodstuffs [113,124].

Similarly, inulin exhibits promising medical applications. It has the potential to reduce the risk of cancer, particularly in preventing colon cancer, and acts as a carrier system for drug delivery in colon diseases [113,124]. Furthermore, it helps in reducing the risk of irritable bowel diseases and relieves constipation [113,124].

3.1.8. Pullulan

Pullulan is a water-soluble polysaccharide with a molecular weight ranging from 5×10^3 to 9×10^6 Da, produced via fermentation by *Aureobasidium pullulans*, a fungus primarily found in soil [36]. Other microorganisms such as *Cytaria* spp., *Teloschistes flavicans*, *Rhodotorula bacarum*, and *Cryphonectria parasitica* have also emerged as promising candidates for large-scale pullulan production [36]. This polysaccharide consists mainly of maltotriose units, which are linearly linked by α -1,4 bonds with α -1,6 linkages branching off [36].

Pullulan is a white powder found abundantly in nature with numerous advantageous properties. It is non-toxic, biodegradable, biocompatible, odorless, tasteless, impermeable to oxygen, and non-hygroscopic [3,36,113]. In addition, pullulan is highly water-soluble and possesses significant water-absorbing capacity [15,36,113]. Moreover, it exhibits thermal

stability, adhesive properties, robust mechanical strength, and resilience to pH changes. Additionally, pullulan is known for its antioxidant, non-mutagenic, non-carcinogenic, and non-immunogenic properties [15,113,131].

Therefore, considering these features, pullulan has an exceptional chemical structure that makes it suitable for forming solid and flexible films and fibers, highlighting its importance in various industries such as food packaging, pharmaceuticals, and cosmetics [15,36]. In fact, pullulan has been used in multiple blends to produce fibers through electrospinning, with bioactive compounds incorporated into these fibers [15]. Furthermore, its remarkable stabilization properties enable pullulan to coat metallic particles effectively [15]. In addition, pullulan has also been observed to form nanogels in water when combined with cholesterol, serving as versatile matrices for entrapping various substances, including growth factors for bone engineering, thereby demonstrating pullulan's potential in advanced drug delivery systems and regenerative medicine [15]. Moreover, its resistance to digestive enzymes makes pullulan suitable for oral delivery, expanding its potential applications in drug delivery systems [15]. Additionally, pullulan's versatility allows it to act as a carrier for genes or proteins, forming biocompatible films suitable for oral consumption [36].

Therefore, pullulan holds promise in biomedical applications, particularly as an ideal carrier for liver drug delivery due to its interaction with lectin receptors in the liver [15]. Furthermore, pullulan and its derivatives are potential candidates for tissue engineering, drug and gene delivery, biomedical imaging, plasma expansion, nasal vaccine adjuvants, and vaccine formulations for tumor treatment [126–128,131]. In cosmeceutical applications, pullulan is used as an ingredient in various cosmetic products such as liquid and paste rouges, eyeliners, eye shadows, hair shampoos, body lotions, hair lacquers, toothpaste, face masks, lipsticks, and hair styling products, creating a rapid film that enhances skin texture and reduces wrinkles, positioning it as a valuable component in anti-aging skincare products [127,128,131].

In the food industry, pullulan serves multiple purposes. It is considered a dietary fiber resistant to human intestinal enzymes like mammalian amylases, making it suitable for low-calorie foods with extended shelf life [113]. Additionally, pullulan's barrier properties make it ideal for packaging films, preserving food freshness [113]. Edible films based on pullulan also carry flavors and antimicrobial substances, enhancing food quality [113]. In addition to its film-forming ability, pullulan acts as a coating agent, improving shelf life and water retention in various food products [128,131].

Moreover, pullulan is widely applied as a viscosity stabilizer and thickening agent, contributing to food texture and thickness [36]. Additionally, pullulan can function as a prebiotic, offering health benefits by promoting the growth of beneficial gut bacteria. Modifications incorporating essential oils, bacteriocins, and plant extracts enhance its effectiveness in food products [128,131].

Furthermore, both ionic and non-ionic pullulan derivatives have demonstrated remarkable efficacy in water purification applications. Recent studies have shown their capability to efficiently remove a wide range of inorganic and organic contaminants from water, including dyes, clay, and pesticides, applying different adsorption and coagulation/flocculation methods [126,128]. Pullulan has also been recognized as a valuable standard in High-Performance Liquid Chromatography (HPLC) for calibrating low-dispersion molecular mass compounds. Moreover, its versatility in gel permeation chromatography as an effective packing material underscores its stability over a wide pH range due to its ionic properties [131]. Besides applications in analytical techniques, recent advances in pullulan research highlight its exceptional potential in electronics and energy production [131].

Therefore, considering these remarkable attributes, researchers are exploring the use of cheaper raw materials such as lignocellulosic biomass and agro-industrial waste like coconut byproducts, beet molasses, grape skin pulp, starch waste, olive oil wastes, and carob pod to promote sustainability in pullulan production [126,128–130]. These materials offer environmentally friendly and economically viable alternatives, contributing to cost-effectiveness and resource efficiency in industrial processes.

3.1.9. Mutan

Mutan is an EPS synthesized by oral bacteria such as *Streptococcus mutans* and *Streptococcus sobrinus* [36]. Its molecular structure comprises α -(1,3)-linked glucose residues in the main chains and α -(1,6) linkages in the side chains [36]. This sticky, colorless, and water-insoluble glucan, characterized by predominant α -1-3 linkages, significantly forms dental biofilms, including dental plaque and caries [4,133].

The structural characteristics of mutan, including its degree of polymerization, branching, and linkage proportions, may vary depending on the organism and type of enzyme involved. Thus, mutan can act as an inducer of mutanase enzymes, which have evolved to hydrolyze α -1-3 glycosidic bonds, facilitating the degradation of dental biofilms. Additionally, mutan is potentially an adsorbent for heavy metals [133].

3.2. Heteropolysaccharide EPSs

3.2.1. Xanthan Gum

Xanthan gum is a versatile heteropolysaccharide derived from *Xanthomonas campestris*, with high molecular weights ranging from 2×10^6 to 2×10^7 Da [5,15]. Its structure consists of a cellulose-like backbone connected via 1,4-linked β -D-glucose residues, interspersed with a trisaccharide side chain comprising two D-mannose units and glucuronic acid. The internal mannose is usually O-acetylated, while the terminal mannose may be associated with a pyruvic acid residue. This unique arrangement confers a high anionic charge to xanthan gum due to the side chains' glucuronic and pyruvic acid groups, resulting in a rigid polymer backbone [5,15,36,113].

Xanthan gum is known for its water solubility, neutrality, non-toxicity, and ability to form highly viscous solutions in cold and hot water at low concentrations [5,113]. Additionally, it exhibits resistance to enzymatic degradation, pH changes, salts, and temperature variations, making it stable in various environmental conditions [36,113]. Xanthan gum's unique properties include pseudoplasticity, biodegradability, cost-effectiveness, and environmental friendliness [5,36,113]. Furthermore, several studies have highlighted its effective antioxidant, antimicrobial, and antitumoral properties, indicating its potential in various applications [16,113]. Moreover, xanthan gum provides viscosifying and stabilizing properties and can act as a coating agent to stabilize different types of nanoparticles, making it a versatile and valuable EPS [15,36,113].

In this sense, xanthan gum is a highly relevant bacterial polysaccharide widely used across various industries due to its exceptional properties. Its versatility and beneficial effects make it indispensable in pharmaceuticals, cosmetics, food, agriculture, oil recovery, textiles, and other sectors [5,36].

In the food industry, xanthan gum is prized for its multifunctional properties, crucial for improving the thickening, stability, and quality of different food products [5,36]. Its FDA approval without restrictions underscores its importance, particularly its emulsifying and stabilizing capabilities [36]. Additionally, xanthan gum is well known as a foam-stabilizing agent and inhibitor of crystal formation in foods [14]. Furthermore, it can reduce oil absorption in deep-fried foods [113].

In addition, xanthan gum has proven valuable in various biomedical fields, including tissue engineering and the development of materials with regenerative and antibacterial properties [5]. It is widely used as a carrier for drugs and proteins and as a scaffold for tablets, cells, or hydrogels in drug delivery systems [16]. Moreover, its unique properties also make it suitable for treating osteoarthritis, mainly through intra-articular injections, and it shows promise as an immune system adjuvant. Additionally, xanthan gum is a hydrogel with antitumor properties used in wound dressings [16].

Furthermore, xanthan gum has diverse applications, including being an eco-friendly absorbent for water decontamination. It is widely recognized as a primary biopolymer for enhancing oil recovery in the petroleum industry. In fact, xanthan gum is pivotal in controlling viscosity during oil drilling processes, significantly boosting oil recovery efforts [5,14]. Moreover, it can also be used in waterborne paints, toothpaste formulations,

and in the production of insecticides, detergents, and cosmetics [14]. Its applications in 3D printing have also garnered attention [5].

However, while xanthan gum is more cost-effective than other microbial polysaccharides, its production can be influenced by several factors, such as the carbon source used in microbial fermentation. This carbon source is vital for energy and is crucial in synthesizing xanthan gum EPS. Hence, alternative media containing various industrial and agricultural wastes have been explored to enhance cost-effectiveness [5]. Promising candidates include carob extract, olive mill water, citrus waste, sugar-beet pulp waste, apple juice residue, corn steep liquor, vegetable scraps, and whey permeates [163].

3.2.2. Alginate

Alginate EPS is a linear heteropolysaccharide composed of d-mannuronic (M) acid and l-guluronic (G) acid subunits, predominantly synthesized by bacteria such as *Pseudomonas aeruginosa* and *Azotobacter vinelandii*, with a molecular weight ranging from 0.5×10^6 to 1.5×10^6 Da [4,14,113]. Despite its bacterial origin, microbial alginate exhibits behavior similar to seaweed-derived alginate. However, microbial alginate typically features a more rigid polymer structure due to longer G-length chains [14]. In addition, the increase in the G-block length results in stronger gels with higher viscosity, especially in the presence of divalent ions such as calcium (Ca^{2+}), thereby influencing its rheological properties [113]. Additionally, alginate EPS is valued for its biocompatibility, biodegradability, and water-holding capacity, making it a versatile biomaterial for biomedicine, pharmaceuticals, cosmetics, and food industries [16,113].

Alginate is widely used in wound healing due to its exceptional swelling and ion exchange capabilities [15]. Furthermore, its ability to form hydrogels of various shapes, such as beads or single pieces, through crosslinking with diverse divalent cations facilitates applications in drug delivery and scaffold production for tissue engineering [14,15,113]. Regarding this, these hydrogels have proven to be effective in encapsulating drugs, growth factors, chondrogenic cells, and human mesenchymal stem cells [15,113]. Additionally, alginate hydrogels are fillers for bone engineering and carriers for osteoinductive factors [15].

In cosmetic formulations, alginate functions as a substance that thickens, forms gels, and serves as an excipient [14]. Moreover, alginate plays a versatile role in the food industry as a viscosity regulator, stabilizer, and packaging material [113].

3.2.3. Hyaluronic Acid

Hyaluronic acid, an anionic heteropolysaccharide with a molecular weight ranging from 1×10^6 to 2×10^6 Da, is mainly synthesized by bacterial strains such as *Streptococcus equi*, *Streptococcus equisimilis*, *Streptococcus pyogenes*, and *Streptococcus thermophilus* [15,36]. Structurally, it consists of alternating N-acetylglucosamine and glucuronic acid units arranged in a linear chain [3,36].

While hyaluronic acid effectively retains water, it exhibits limited mechanical stability. Moreover, it demonstrates remarkable biocompatibility, non-immunogenicity, anti-inflammatory properties, and excellent moisture absorption capabilities. Its viscoelastic nature provides flexibility, and its degradation does not produce harmful byproducts. Additionally, hyaluronic acid forms highly non-Newtonian solutions with gel-like properties due to its water solubility and exhibits viscoelastic behavior, facilitating gel formation with various crosslinkers [15,16]. Furthermore, hyaluronic acid is widely recognized as a crucial component of the extracellular matrix in various tissues, including the vitreous body, skin, and arthrosis. In this way, owing to its exceptional biological properties, it is extensively used in the cosmetic, medical, and pharmaceutical industries [14,15,36].

In skincare and cosmetics, hyaluronic acid is a moisturizing agent integral for formulating pharmaceuticals and artificial tear solutions [14,36]. Furthermore, it has shown potential in cancer treatment, angiogenesis, wound healing, and cell motility modulation, along with its ability to induce the expression of inflammatory mediators. Moreover, its capability to enhance cell adhesion and proliferation also makes hyaluronic acid advantageous for

tissue engineering scaffolds despite challenges related to the mechanical properties of such scaffolds.

In medical applications, hyaluronic acid treats osteoarthritis, substitutes eye fluid in ophthalmic surgeries, and acts as a joint lubricant to replace the synovial fluid. Additionally, it is also utilized in surgical procedures to prevent abdomen adhesion and as a surface coating [14–16].

Furthermore, hyaluronic acid is recognized as an ingredient in dietary supplements and health food additives, contributing to its versatile applications and driving the development of eco-friendly production methods [164]. To enhance accessibility and promote responsible resource usage, sustainable approaches using agro-industrial byproducts such as corn steep liquor and sugarcane molasses have been explored for hyaluronic acid production [165,166].

3.2.4. Kefiran

Kefiran, a water-soluble polysaccharide produced by various lactic acid bacteria from kefir grains, is recognized as safe for consumption. Key producers include *Lactobacillus kefir*, *Lactobacillus parakefir*, *Lactobacillus kefiranofaciens*, *Lactobacillus kefirgranum*, and *Lactobacillus delbrueckii* subsp. *Bulgaricus* [4,113,167]. This EPS has garnered attention for its unique composition and potential health benefits. Kefiran primarily comprises D-galactose and D-glucose residues in nearly equal proportions, forming a glucogalactan structure with a molecular weight ranging from 50 to 15,000 kDa, influenced by factors such as the carbon source, isolation conditions, and purification methods [16,113]. In this respect, optimal production conditions for kefiran involve the careful control of the carbon source, pH, and temperature. Several studies have identified lactose as the most effective carbon source, with the highest kefiran yield typically achieved at 20–30 °C and pH values of 5 to 6 [16].

Kefiran exhibits several remarkable properties, making it a promising biomaterial for various biomedical and food applications. In its solid state, kefiran is a semi-crystalline polymer with notable resistance to hydrolysis [16]. Moreover, kefiran can form a gel in aqueous solutions containing ethanol, further expanding its potential applications [16]. It can also produce both translucent gels and transparent films during cryogenic treatment, further highlighting its adaptable nature [113]. However, to enhance the flexibility of kefiran-based films, plasticizers such as glycerol and sorbitol are commonly applied at low concentrations [113,167].

In particular, kefiran films have demonstrated excellent water vapor barrier properties, making them suitable for various coating and packaging applications, particularly in developing edible biofilms [113,167]. Furthermore, some studies suggest that kefiran exhibits antibacterial and antioxidant properties and promotes cell adhesion and proliferation, emphasizing its versatility and potential for biomedical applications [16]. These applications include controlled drug and probiotic delivery, and antitumor and mucosal adjuvant properties [16,139,140]. Kefiran-based scaffolds have shown promise in tissue engineering, and kefiran-loaded nanofibers have been used for wound dressing applications [16,139]. Moreover, kefiran is widely used for biodegradable and edible food packaging and stabilization and could serve as a food-grade thickener in fermented dairy products [113,139,140].

However, despite kefiran's potential, production costs remain high due to expensive carbon and organic nitrogen sources like sugars, tryptone, yeast extract, and meat extract. Alternative low-cost sources have been proposed for cost-effective kefiran synthesis to address this challenge. These include byproducts from agricultural industries, such as whey lactose and mature coconut water from cheese and coconut milk production, spent yeast cells from breweries, proteins derived from whey during cheese production, and nitrogen sources obtained from soybean processing [168].

3.2.5. Gellan

Gellan gum, an anionic and linear EPS obtained from the aerobic fermentation of *Sphingomonas paucimobilis*, has a molecular weight ranging from 5×10^3 to 2×10^6 Da [15].

It mainly consists of repeating units of four sugars: β -D-glucose, β -D-glucuronic acid, β -D-glucose, and α -L-rhamnose, with acetyl and glyceryl groups bonded to the glucose residues [14,16,36,113]. These substituents impart unique properties to gellan gum, including resistance to enzymatic degradation and stabilization of emulsions and suspensions [14]. Additionally, acetyl groups enhance solubility in hot water, facilitating dispersion in aqueous systems [14,16,36]. Moreover, the acetyl residues enable the formation of robust, soft, elastic, and thermo-reversible gels at low concentrations through heating and cooling from 65 °C [14,16,113]. In turn, diacylation of native gellan gum results in rigid and brittle gels forming below 40 °C, leading to improved thermal stability [14,16]. Furthermore, this EPS also shows reduced susceptibility to pH changes compared to other hydrocolloids [36].

Therefore, gellan gum's remarkable rheological properties make it suitable for various fields, including food, pharmaceuticals, and environmental bioremediation [14]. It is non-toxic, FDA-approved, and plays a crucial role in diverse food applications as a stabilizer, binder, thickener, and gelling agent, contributing to the quality and consistency of various foods. Gellan gum is a reliable gelling agent in desserts and jams, providing firmness without compromising texture [36,113]. Moreover, it enhances the texture and flavor release in jellies and ice creams, acting as a bulking agent. Beyond texture modification, gellan gum is a carrier for vitamin C and a matrix for encapsulating heat-sensitive ingredients such as probiotic bacteria and essential fatty acids, offering protective encapsulation for controlled release and stability [36,113].

In pharmaceuticals, gellan gum is integral to hydrogel formation for controlled drug release, supporting cell adhesion, proliferation, and differentiation on its surface, which makes it promising for tissue engineering applications [14,15]. It forms particles and polyelectrolyte complexes that effectively delay drug release, and as an excipient, aids in the controlled disintegration of tablets in oral, ophthalmic, and nasal drug formulations [14]. Furthermore, its capacity to encapsulate different drugs and materials enhances cell proliferation and enables diverse delivery methods [15]. Additionally, gellan gum is used in various paper coatings in the paper industry as well as in other sectors, where it serves as a water flocculent and is helpful in the bioremediation of contaminated soils and aquifers [14].

Nevertheless, gellan gum is often incorporated into blends or composites due to its low mechanical resistance and high polyelectrolyte content [14,15]. Despite its numerous applications and versatile properties, production challenges persist, particularly in cost and resource utilization. To enhance gellan production and promote environmental sustainability, researchers have explored alternative feedstocks such as molasses and cheese whey-based medium, and biodiesel-derived waste glycerol (WG) as the primary carbon source [169,170].

3.2.6. Emulsan

Emulsan is a versatile EPS produced by *Acinetobacter* species, including *Acinetobacter venetianus* and *Acinetobacter calcoaceticus*. It exhibits amphiphilic properties due to its molecular structure, which comprises a sugar backbone with fatty acid branches, notably α - and β -hydroxydodecanoic acid [36,142–144]. This unique chemical composition can be modified to produce emulsans with diverse chemical and biological properties [36,144]. Moreover, its amphiphilic nature makes it suitable for various applications, particularly as a bioemulsifier in forming stable hydrocarbon-in-water emulsions [143]. Therefore, emulsan holds significant value in industrial and environmental settings, with potential applications in biotechnology, food processing, and environmental remediation. Recent advancements have led to the development of emulsan-based nanoparticles for drug delivery [142].

Furthermore, emulsan is an effective emulsifier for oily substances, making it useful in cleaning, degreasing, and maintenance applications across several industries, including crude oil recovery, cosmetics, and personal care products. These products include cleansing creams, lotions, shampoo, soap, and toothpaste [36,143]. Additionally, emulsan is employed as an emulsifier and vaccine adjuvant [14].

In addition to its versatile applications in various industries, agricultural oils have been explored as a cost-effective carbon source for producing emulsan from renewable resources [145,171].

4. Emergent Functionalities and Applications of Exopolysaccharides (EPSs)

EPSs display unique properties that render them valuable across various fields, including food and beverage production, pharmaceuticals, cosmetics, wound healing, tissue engineering, agriculture, and environmental remediation, as described in Section 3. These properties enable EPSs to serve as thickeners, stabilizers, and emulsifiers in food products, enhancing texture and stability. EPSs also improve the biocompatibility of biomedical devices and offer moisturizing and antioxidant benefits in cosmetic formulations. Moreover, EPSs present promising applications in bioremediation by adsorbing heavy metals and pollutants, in textile finishing by imparting stain and water resistance or antimicrobial attributes, and in environmental protection through biodegradable materials. In agriculture, EPSs act as biofertilizers, improving soil health and crop yield.

Additionally, EPSs are being explored in advanced nanotechnology to create innovative materials and solutions, underscoring their versatility and significance across various industrial and research domains [10,35,59,60,68,71,74–76,92]. This recognition of their properties and potential uses has prompted researchers to isolate new EPS-producing bacteria in search of EPSs with unique and distinctive functions. This endeavor is expected to yield new potential applications across different sectors and allow for the development of EPS functional materials with attractive but still poorly explored properties (Table 3).

Among the more recent EPSs produced by bacteria, *Deinococcus radiodurans* has captured significant attention of different researchers due to its remarkable resistance to extreme environmental conditions, such as ionizing radiation, UV radiation, dehydration, and oxidative stress [83,172]. This resilience is attributed to its efficient DNA repair mechanisms and robust antioxidant systems [80,172]. In addition, the EPS produced by *Deinococcus radiodurans*, known as DeinoPol, further enhances its resilience by suppressing the formation of *S. aureus* biofilms [83,172]. Moreover, DeinoPol isolated from a novel strain, *Deinococcus radiodurans* BRD125, has been shown to reduce irradiation-induced apoptosis, highlighting its potential as an effective radioprotective agent [173].

Similarly, an aqueous-soluble EPS obtained from the *Pantoea agglomerans* strain KFS-9 has demonstrated radioprotective properties by scavenging free radicals [37,174]. Furthermore, EPSs isolated from *Ecklonia cava* fermented by *Lactobacillus brevis* have significantly enhanced cell survival and proliferation in γ ray-irradiated cells. This effect is attributed to their ability to scavenge free radicals, particularly reactive oxygen species (ROS), which can cause cellular tissue damage and lead to mortality. Thus, the antioxidant activities of these EPSs hold promise for mitigating the harmful effects of radiation exposure [37,175].

Therefore, the biosynthesis of EPSs from radioresistant bacteria presents a promising avenue for developing novel and effective radioprotective materials for therapeutic and cosmetic applications [37]. This emphasizes the importance of further exploring EPS applications, including various bacterial sources and their benefits. For example, a study isolated CV5-EPS from a radioresistant strain, *Bacillus siamensis* CV5, obtained from irradiated roots of *Cistanche violacea*. The analysis revealed that the purified CV5-EPS comprised rhamnose, fructose, mannose, and glucose. Moreover, CV5-EPS was found to be radiation-inducible and exhibited radioprotective and antioxidant properties against ROS. Furthermore, its antioxidant activity significantly increased with the irradiation dose ($p < 0.01$), as demonstrated by DPPH, ABTS, and FRAP assays, indicating potential benefits as a gel in cancer radiotherapy in order to minimize damage to surrounding healthy tissues [37].

A novel EPS-designed EPS-M1 was obtained from the fermentation medium of *Bacillus* sp. QDR3-1. This EPS is biocompatible and effective in protecting cells from UV radiation damage by regulating levels of ROS, mitochondrial membrane potential (MMP) depolarization, and the activity of apoptotic enzymes such as Caspase-3/7. Additionally, its rich

mannose content also suggests excellent antioxidant activity and resistance to UV-induced stress [176].

Moreover, EPS from the *Rhodococcus pyridinivorans* ZZ47 strain has demonstrated antioxidant activity without genotoxicity, suggesting its suitability for various sectors and industrial applications. Meanwhile, EPS produced by *Paenibacillus polymyxa* PYQ1 has shown potential as a protective agent in skincare, offering benefits against short-wave UV radiation (100–280 nm), which is known to induce cytotoxicity in HaCaT cells [177,178].

Furthermore, other EPSs with potential benefits in mitigating the harmful effects of radiation exposure have been investigated, highlighting their significant antioxidant activity, a characteristic closely linked to their radioprotective properties, as previously discussed [43]. Concerning this, *Geobacillus* sp. TS3-9, a radioresistant bacterium isolated from a radon hot spring, produced an EPS with notable capabilities in scavenging hydroxyl, superoxide, and DPPH (2,2-diphenyl-1-picrylhydrazyl) radicals [37]. In addition, *Anoxybacillus* sp. R4-33, a thermophilic bacterium resistant to ionizing radiation and isolated from radon hot springs in China, synthesized an EPS with antioxidant properties. This EPS demonstrated the ability to adsorb heavy metals from water solutions, underscoring its versatility and potential as a valuable bioresource for industrial applications [37]. In this way, researchers have recently identified new EPSs from extremophilic bacteria, including thermophiles, alkalophiles, and halophiles, due to their remarkable protective properties against environmental stresses (Figure 8) [10,13,35,37–40,52,57,73,74,78,84,95,96,110].

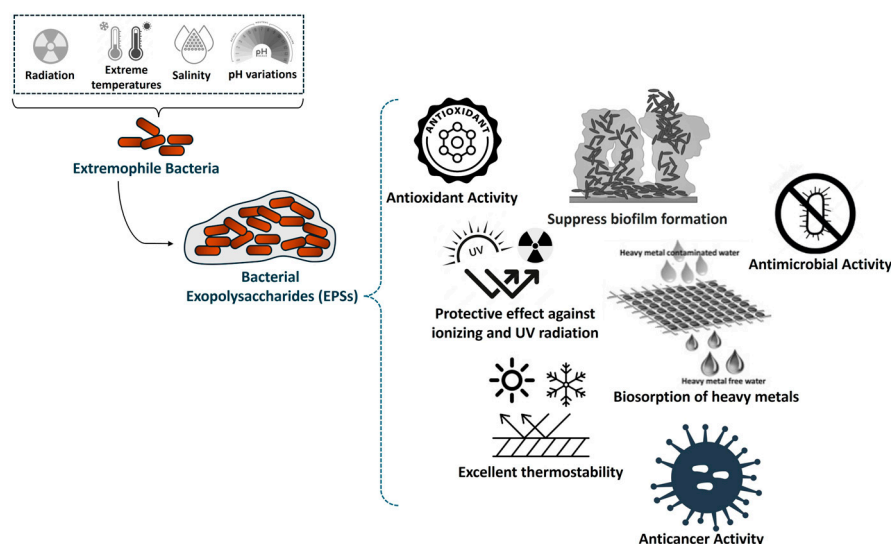


Figure 8. Illustration of the functional properties achieved by EPSs from extremophilic bacteria.

For example, the thermophilic bacterium *Geobacillus* sp. strain WSUCF1 produced two EPSs with a molecular weight of around 1000 kDa. The EPSs demonstrated remarkable thermostability, non-toxicity to HEK-293 cells, and antioxidant activity. These properties suggest their potential for meeting the demand for natural polysaccharides in future biomedical applications, such as drug carriers [37].

Nonetheless, despite the relatively limited exploration of thermophile EPSs, evidence suggests that these biopolymers exhibit properties with significant potential for industrial applications. Further research and systematic screening of EPSs from thermophiles, along with advances in understanding microbial EPS synthesis, promise to uncover novel biopolymers of considerable interest and value across a wide range of applications [18,39,44,50,51,60,61,69,94,103,104,107–109].

Similarly, psychrotrophic and psychrophilic bacteria have garnered significant attention for EPS production [46,53,67]. For example, Ali et al. investigated EPS production by the cold-adapted *Pseudomonas* sp. BGI-2 [179]. Their findings revealed that this EPS exhibited notable characteristics in a membrane protection assay using human red blood

cells (RBCs). Furthermore, the EPS demonstrated significant cryoprotective effects against a mesophilic *Escherichia coli* k12 strain, comparable to 20% glycerol.

Moreover, pretreatment *Escherichia coli* k12 with the EPS enhanced the inhibition of lipid peroxidation in vitro. Therefore, based on these data, the EPS produced by *Pseudomonas* sp. BGI-2 shows promise for applications across various fields [179].

Additionally, the potential of EPSs from halophilic bacteria to develop new functional materials represents a promising avenue for further research and development [17,26,27,31,32,45,55,58,59,66,70,74,87,88,90,100,102,106,107,180]. For instance, Radchenkova et al. synthesized an extracellular polymer from the halophilic bacterium *Chromohalobacter canadensis* 28, isolated from Pomorie salterns [181]. Notably, *Chromohalobacter canadensis* 28 demonstrated the highest level of extracellular polymer synthesis at a high NaCl concentration (15% w/v). Subsequent chemical analysis of the purified extracellular polymer revealed two main fractions: an EPS fraction containing glucosamine, glucose, rhamnose, xylose, and unidentified sugars, and a protein fraction predominated by polyglutamic acid (PGA). The resulting hydrogel, formed by the combination of PGA and EPS fractions, exhibited excellent functional properties such as high hydrophilicity, swelling behavior, stabilizing and emulsifying properties, and good foaming capability, highlighting its promising potential for application in the cosmetics industry [181].

In another study, Joulak et al. reported the production and structural analysis of a novel heteropolysaccharide named EPS-K2, derived from the highly halophilic bacterium *Halomonas smyrnensis* K2 [182]. This EPS-K2 was mainly composed of mannose, glucose, and galactose and exhibited remarkable thermostability, making it suitable for thermal processes. Moreover, EPS-K2 demonstrated effective antioxidant activity, iron-chelating ability, and DNA protection and showed significant inhibitory effects against *Enterococcus faecalis* and *Escherichia coli* and their biofilm formation, suggesting potential applications in food, biomedicine, and pharmaceutical industries [182].

Furthermore, alkalophilic bacteria also exhibit distinctive properties. For example, an alkaliphilic bacterium, *Cronobacter sakazakii*, was employed to produce a biosurfactant. The results demonstrated that the biosurfactant exhibited low viscosity with pseudoplastic rheological behavior and significant emulsification activity with oils and hydrocarbons [183].

Additionally, researchers have explored the capabilities of haloalkaliphilic bacteria [47]. For example, Arayes et al. investigated an EPS produced by a haloalkaliphilic bacterium, *Alkalibacillus* sp. w3, which was isolated from a salt lake [184]. The EPS generated by *Alkalibacillus* sp. w3, comprising carbohydrates, proteins, and lipids, exhibited promising functional properties. It showed significant anticancer activity against HepG2 and HCT-116 cell lines and antibacterial activity against various bacteria and yeast, highlighting its potential for medical applications [184].

Furthermore, acidophilic bacteria, such as *Bacillus xiamenensis* RT6 isolated from a highly acidic environment, produced a heteropolysaccharide (EPS_t) composed of glucose, mannose, and galactose with an average molecular weight of 2.71×10^4 Da [185]. Results obtained by Huang-Lin et al. indicated that EPS_t presents antioxidant properties, enhancing cell viability. Moreover, it demonstrated metal chelation abilities, particularly in reducing the concentration of transition metals like iron at high concentrations [185]. Additionally, EPS_t efficiently emulsified various natural polysaccharide oils, achieving up to 80% efficiency, particularly with olive and sesame oil, making it a promising alternative to environmentally harmful emulsifiers. These findings underscore the potential of EPS_t in pharmaceutical and industrial applications [185].

Nevertheless, despite the unique properties and applications demonstrated by EPSs produced by extremophilic bacteria, the literature has not extensively explored them [10,38–40,77–79,184]. Therefore, further research into these characteristics will support the development of new functional materials with enhanced properties for diverse applications. This underscores the importance of investigating the potential of EPSs in various fields.

Corrosion inhibition is one such area where EPSs show promising applications. For instance, Moradi et al. assessed the efficacy of EPS derived from *Vibrio neocaledonicus* sp. in

mitigating carbon steel corrosion in artificial seawater and acidic environments. The EPS composition was diverse, containing polysaccharides, nucleic acids, and proteins, with an average molecular weight of 29,572 Da [186]. The corrosion inhibition mechanism involved EPS adsorption onto the metal surfaces, forming Fe-EPS complexes that acted as barriers, preventing oxygen penetration and delaying both anodic and cathodic reactions. The inhibitory effect increased with higher EPS concentrations and prolonged exposure times. Remarkably, the study reported a significant corrosion inhibition rate of 95.1% using 10 g/L of EPS concentration after five days of exposure to seawater. This finding underscores the considerable potential of EPSs as green inhibitors for corrosion protection in various environments [186].

Additionally, EPSs exhibit diverse beneficial properties beyond corrosion inhibition. For example, the EPS produced by *Rhodococcus erythropolis* HX-2 (HPS) demonstrated promising anticancer properties by inhibiting the growth of cancer cells at specific concentrations without harming normal cells [187]. Comprising glucose, galactose, fucose, mannose, and glucuronic acid, HPS exhibited higher viscosity at equivalent concentrations than commercially available guar gum, indicating a superior thickening capacity for excipient applications in the food and medicine industries. Moreover, with its small pore size ($<1\ \mu\text{m}$) and dense distribution, HPS effectively retains moisture, enhancing its versatility for various industrial uses such as gelling, thickening, emulsifying, stabilizing, and water-binding [187]. Thus, based on these physical and chemical properties, HPS holds potential for applications in the food industry as a bio-thickener, additive, stabilizer, or viscosifying agent, underscoring its value across industrial and pharmaceutical sectors [187].

Therefore, EPSs exhibit diverse functions and applications, proving valuable across industries ranging from pharmaceuticals to environmental protection while demonstrating potential for innovation across multiple fields. Extremophile EPS shares typical market applications with EPS from other microorganisms, particularly in food, pharmaceutical, and cosmetics sectors. However, extremophile EPS is critical in specialized markets that require exceptional stability and unique bioactivities under extreme conditions, making them essential in advanced biotechnology, environmental biotechnology, and specialized industrial applications [10,16,35,42,43,48,54,56,57,63,64,68,73,81,82,85,93,97,101]. Moreover, exploring new EPS-producing bacteria underscores ongoing efforts to unlock their full potential, promising novel applications and functional materials.

Table 3. Some underexplored EPSs and their functional properties. N.A.: Not available.

Producer Organism	EPS	Sugar Carbon Source	Monosaccharide Composition	Molecular Weight (Da)	Functional Properties	Refs.
<i>Deinococcus radiodurans</i>	DeinoPol	Glucose, fructose, galactose, rhamnose, fucose, arabinose, mannose, and xylose	Xylose, galactose, fucose, glucose, arabinose, and fructose	8.0×10^4 – 1.0×10^5	Tolerance to ionizing radiation, UV radiation, desiccation, and oxidizing agents; robust antioxidant effects; ability to suppress <i>Staphylococcus aureus</i> biofilm formation; radioprotection.	[188]
<i>Pantoea agglomerans</i> KFS-9	WSEPS	N.A.	Arabinose, glucose galactose, and gulcuronic acid	7.6×10^5	High antioxidant activity; protective effect against UV radiation.	[174]
<i>Lactobacillus brevis</i> -fermented <i>Ecklonia cava</i>	VLFEF	N.A.	Fucose, glucose, and mannose	$>3.0 \times 10^4$	Enhanced cell survival and proliferation in γ ray-irradiated cells; antioxidant activity; radioprotective effects.	[175]
<i>Bacillus siamensis</i> CV5	CV5-EPS	Glucose	Rhamnose, fructose, mannose, and glucose	N.A.	Protective mechanism against radiation-induced damage; antioxidant activity.	[37]
<i>Bacillus</i> sp. QDR3-1	EPS-M1	Glucose	Mannose, glucose, galactose, and fucose	3.38×10^4	Biocompatible; protection against UV radiation; resistance to UV-induced stress; antioxidant activity.	[176]
<i>Rhodococcus pyridinivorans</i> ZZ47	N.A.	Glucose	N.A.	N.A.	Antibiofilm activity; anti-angiogenic properties; antioxidant activity with no genotoxicity	[177]
<i>Paenibacillus polymyxa</i> PYQ1	N.A.	Sucrose	N.A.	N.A.	Protection against short-wave UV radiation.	[178]
<i>Geobacillus</i> sp. TS3-9	N.A.	Glucose, lactose, galactose, xylose, maltose, fructose, mannose, sucrose, and sorbose	D-mannose, D-glucose, and rhamnose	3.2×10^6	Radiation resistance; antioxidant activity.	[189]
<i>Anoxybacillus</i> sp. R4-33	EPS-II	Glucose	D-mannose and D-glucose	1.0×10^6	Biosorption of heavy metals; antioxidant properties.	[37,190]

Table 3. Cont.

Producer Organism	EPS	Sugar Carbon Source	Monosaccharide Composition	Molecular Weight (Da)	Functional Properties	Refs.
<i>Geobacillus</i> sp. WSUCF1	EPS-1 EPS-2	Glucose	EPS-1: mannose and glucose; EPS-2: mannan	1.0×10^6	Antioxidant activities; non-cytotoxicity; excellent thermostability.	[69,70]
Cold-adapted <i>Pseudomonas</i> sp. BGI-2	N.A.	Glucose, galactose, mannose, mannitol, glycerol, and molasses	Glucose, galactose, and glucosamine	N.A.	Protect cell membranes; cryoprotective effect.	[179]
<i>Chromohalobacter</i> <i>canadensis</i> 28	N.A.	Lactose	Glucosamine, glucose, rhamnose, xylose, and not identified sugar	$>1.0 \times 10^6$	High hydrophilicity; high swelling behavior; stabilizing properties; emulsifying properties; good foaming ability.	[181]
<i>Halomonas smyrnensis</i> K2	EPS-K2	Glucose	Mannose, glucose, and galactose	3.96×10^5	Remarkable thermostability; antioxidant activity; iron-chelating ability; DNA protection; antimicrobial activity; anti-biofilm activity.	[182]
<i>Alkalibacillus</i> sp. w3	N.A.	Glucose, fructose, maltose, galactose, mannitol, sucrose, and lactose	N.A.	N.A.	Anticancer activity; antibacterial activity.	[184]
<i>Bacillus xiamenensis</i> RT6	EPS _t	Glucose	Glucose, mannose, and galactose	2.71×10^4	Antioxidant properties; metal chelation abilities.	[185]
<i>Vibrio neocaledonicus</i> sp.	N.A.	Glucose, sucrose, fructose, xylose, mannitol, and galactose	N.A.	2.96×10^1	Corrosion inhibition.	[186]
<i>Rhodococcus erythropolis</i> HX-2	HPS	N.A.	Glucose, galactose, fucose, mannose, and glucuronic acid	1.04×10^6	Anticancer properties; moisture retention.	[187]

5. Challenges and Future Research Directions

Despite the promising applications and functionalities of EPSs, several challenges and future research directions must be addressed to ensure their successful implementation and widespread adoption, as illustrated in Figure 9.

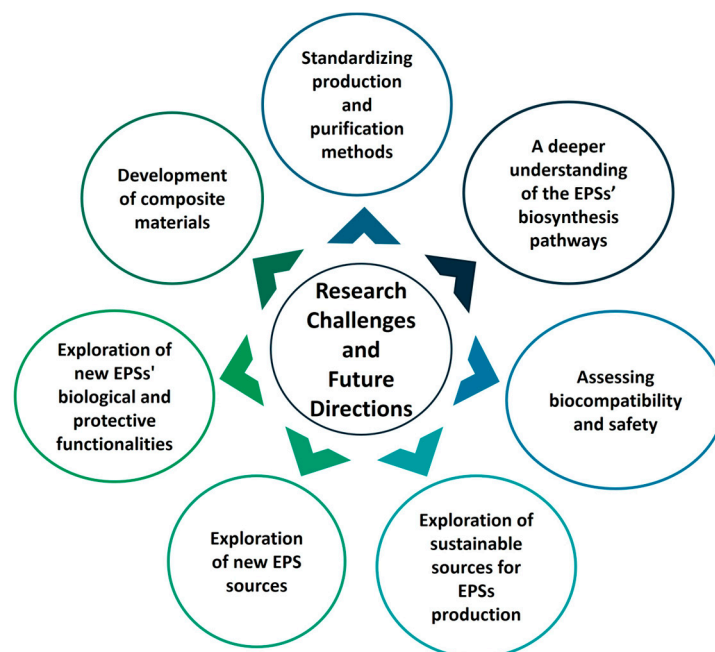


Figure 9. Illustrative representation of the research challenges and future directions for the development of the functional EPS materials.

Efforts to overcome the challenges in the large-scale EPS production are imperative. Thus, standardizing production and purification methods is crucial to enhance industrial reproducibility and scalability. Moreover, gaining deeper insights into the biosynthesis pathways of EPSs from different bacterial strains can optimize genetic modifications, potentially increasing EPS yields and enabling the customization of materials' functionalities. Furthermore, understanding the unique biosynthesis pathways and sugar residues synthesized by fungi, yeasts, and microalgae could expand the range of EPS functionalities and applications across various industries.

Recent studies have focused on addressing the variability and complexity of EPS production methods. Bibi et al. (2021) investigated methods to standardize production and purification techniques for EPS derived from *Lactobacillus* species, emphasizing the optimization of biosynthesis pathways and genetic modifications to improve EPS yields and functionality [191]. Similarly, Xiong et al. (2023) explored the structural and functional relationships of EPSs synthesized by lactic acid bacteria, highlighting the potential for developing high-value biopolymers [191,192].

However, implementing these advancements faces several limitations. Achieving consistent industrial-scale production of EPSs remains challenging due to the diverse requirements of different bacterial strains and the complexity of biosynthesis pathways. Technical hurdles in scaling up production processes and ensuring cost-effectiveness with new techniques also present significant barriers [63].

To address these challenges, ongoing research should prioritize overcoming the technical and regulatory hurdles that hinder the industrial application of EPS production methods. Additionally, exploring alternative approaches, such as novel fermentation strategies or advanced bioreactor designs, could provide more efficient and scalable production pathways.

Moreover, economic feasibility remains a pivotal issue in EPS production. Regarding this, several studies have investigated the use of low-cost agricultural and industrial wastes as alternative raw materials, demonstrating significant cost reduction and enhanced sustainability. Integrating these alternative raw materials not only addresses economic challenges but also aligns with the environmental goals by promoting the use of renewable resources [17,21,23,51,75,87,106].

In addition to economic considerations, ensuring the biocompatibility and safety of EPSs is crucial for their acceptance, particularly in critical sectors such as biomedical and food industries. Recent studies have emphasized rigorous assessments of EPSs' toxicity profiles and regulatory compliance to meet industry standards [2].

Looking ahead, future research should continue exploring extremophilic bacteria to find EPSs with unique functionalities, such as radiation protection and resistance to extreme conditions. Likewise, investigating their biological activities, including antimicrobial, antioxidant, and anticancer properties, could expand the potential applications of EPSs. To achieve this, exploring advanced manufacturing techniques, such as electrospinning and 3D printing, offers innovative ways to incorporate EPSs into functional materials, enabling the customization of material properties and expanding their applications across various industries.

Moreover, integrating EPSs with other materials could drive the development of composite materials with enhanced properties, paving the way for a new generation of functional EPS materials.

Hence, while challenges in EPS production and application persist, ongoing research efforts and technological advancements provide promising solutions. Addressing these challenges will enhance the industrial feasibility of EPSs and expand their potential applications across diverse sectors.

6. Conclusions

EPSs represent a captivating group of carbohydrate biopolymers synthesized by microorganisms in response to harsh environmental conditions. Their distinct advantages over synthetic polymers, such as biodegradability and eco-friendliness, make them invaluable in various industries, including biomedical, pharmaceutical, cosmetic, food, and others. Moreover, the versatility of EPSs in adopting diverse structures enhances their efficacy as thickeners, stabilizers, encapsulating agents, and numerous other roles due to their remarkable biocompatibility and bioactive properties. For example, notable microbial EPSs like dextran, bacterial cellulose, curdlan, levan, pullulan, xanthan gum, hyaluronic acid, and gellan have already demonstrated significant functional properties and found widespread applications.

However, recent studies underscore the promising potential of EPSs sourced from extremophile bacteria, revealing novel protective functionalities such as radiation protection and resistance to extreme conditions. Further exploration of their biological activities, including antimicrobial, antioxidant, and anticancer properties, promises to uncover additional benefits and expand their value across diverse fields.

Despite the advancements achieved so far, addressing several critical challenges and future research directions is essential to fully harness the advantages of EPSs and ensure their widespread implementation. Essential steps include standardizing production methods, optimizing biosynthesis pathways across different microbial strains, and exploring novel microbial sources. Additionally, integrating EPSs with other materials to enhance their functionalities represents another promising avenue for developing a new generation of functional materials with tailored properties.

Furthermore, exploring the utilization of waste or alternative feedstocks offers a sustainable approach to mitigate the high production costs associated with EPSs, thereby promoting economic viability alongside environmental management. Future research should also focus on advancing EPS-based materials through innovative manufacturing

techniques such as electrospinning and 3D printing, which enable precise control over material properties and thereby expanding their applications.

Looking forward, the future of EPS research increasingly aligns with principles of sustainability and the circular economy. As global awareness of environmental impact grows, there is a pressing need to develop EPS production methods that minimize energy consumption and waste generation. Innovations in bioprocess engineering and biorefinery concepts offer potential solutions by optimizing resource utilization and maximizing product yields from microbial fermentation. Furthermore, integrating EPSs into bio-based composites and functional materials holds promise for creating new generations of sustainable products with enhanced performance characteristics tailored to specific applications. Through these advancements, EPSs can facilitate the creation of more environmentally friendly and resource-efficient industries, promoting a balanced relationship between technology and environmental responsibility.

Hence, this review paper highlights the significance of EPSs in advancing industrial and scientific domains. By addressing current challenges and exploring new frontiers, EPS research holds great promise for developing sustainable and practical solutions that encompass the diverse needs of industries while promoting environmental sustainability.

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