2 Exopolysaccharides: Production and Application in Industrial Wastewater Treatment

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Abstract

In recent decades, polysaccharide molecules of plant, bacterial, and fungal origin have been extensively researched due to their multi-functionality. Various kinds of polysaccharides produced by plants, viz., cellulose, pectin, and starch; algae, viz., agar, alginate, and carrageenan; and bacteria, viz., alginate, dextran, gellan, pullulan, and xanthan gum), are commonly used as food additives for their gelling, stabilizing, or thickening properties (Sutherland IW. Microbiology-SGM 147:3–9, 2001a). Both prokaryotes and eukaryotes are able to produce exopolysaccharides (EPSs); prokaryotes such as eubacteria and archaebacteria and eukaryotes such as phytoplankton, fungi, and algae have now got more research attention (Houghton J, Quarmby J, Stephenson T. Water Sci Technol 44(2):373–379, 2001). Bacteria carry the EPS as their metabolic products which accumulate on the cell surface (Kumar AS, Mody K, Jha B. J Basic Microbiol 47:103–117, 2007a). The composition of EPS has a variety of organic and inorganic substances which have structural variable like either homopolysaccharides such as dextran, mutan, and levan or heteropolysaccharides. Application of various nano material, prepared as bionanoparticles, helpful to treat industrial waste water.

Keywords

Exopolysaccharide · Prokaryotic polysaccharide · Eukaryotic polysaccharide · Bionanopaticles · Industrial waste water treatment

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2.1 Introduction

In recent decades, polysaccharide molecules of plant, bacterial, and fungal origin have been extensively researched due to their multi-functionality. Various kinds of polysaccharides produced by plants, viz., cellulose, pectin, and starch; algae, viz., agar, alginate, and carrageenan; and bacteria, viz., alginate, dextran, gellan, pullulan, and xanthan gum), are commonly used as food additives for their gelling, stabilizing, or thickening properties (Sutherland 2001a). Both prokaryotes and eukaryotes are able to produce exopolysaccharides (EPSs); prokaryotes such as eubacteria and archaebacteria and eukaryotes such as phytoplankton, fungi, and algae have now got more research attention (Houghton et al. 2001). Bacteria carry the EPS as their metabolic products which accumulate on the cell surface (Kumar et al. 2007a). The composition of EPS has a variety of organic and inorganic substances which have structural variable like either homopolysaccharides such as dextran, mutan, and levan or heteropolysaccharides. Application of various nano material, prepared as bionanoparticles, helpful to treat industrial waste water.

Perhaps, biomolecules from plants now have captured the commercial market for their ease of availability and cost-effective purification process. But renewability, stable cost, and constant and reproducible physicochemical properties of the microbial polysaccharides have provided them an edge over the macromolecules of plant origin, although only few of them have been commercialized so far (Poli et al. 2009; Reichhardt and Cegelski 2014). Exopolysaccharides (EPS) are polymers excreted by some microorganisms as a protective barrier against harmful conditions. Many microbial EPS, such as xanthan or gellan gums, isolated from terrestrial sources are being successfully exploited in several industries. Indeed, EPS can be used in a wide range of biotechnological applications, such as thickening agents, stabilizers, and texturizers in the food industry, flocculating agents in the wastewater treatment industry, or anti-aging molecules in the cosmetics industry.

EPSs have a significant influence on the physicochemical properties of microbial aggregates, including structure, surface charge, flocculation, settling properties, dewatering properties, and adsorption ability. EPSs bind with cells through complex interactions to form a vast net-like structure with plenty of water that protects cells against dewatering (Sutherland 2001a) and the harm of toxic substances. Part of EPS can serve as carbon or energy sources in conditions of nutrient shortage (Banik et al. 2007; Manjamadha and Muthukumar 2016). They also accelerate the formation of microbial aggregates through binding cells closely (Lepek and D'Antuono 2005). Thus, the in-depth study of EPS is a matter of great interest not only in terms of improving our comprehension of biological wastewater treatment, but also improving the efficiency of such treatment through the optimization of operational parameters.

Bacterial cells are capable to produce two different types of extracellular polysaccharides which bind either to the bacterial cell surface tightly, defined as capsular polysaccharides (CPS), or they can be excreted into the extracellular surrounding environment, described as exopolysaccharides (EPS) which can be lightly attached to the bacterial cells or totally detached from the bacteria. A large and growing body of literature has labelled these two types of extracellular polysaccharides with the

Table 2.1 Microbial EPS and its structure

Bacteria	EPS	Chemical structure
Pseudomonas aeruginosa, *Pseudomonas putida*	Alginate	β-1,4-linked mannuronic and α-1,4-linked guluronic acids
Acetobacter xylinum	Bacterial cellulose	β-1,4-linked glucose
Sphingomonas paucimobilis	Gellan	β-d-glucuronic acid-1,4-β-d-glucose-1,4-β-l rhamnose
Leuconostoc mesenteroides	Dextran	α-1,6-linked glucose; some 1,2-, 1,3-, or 1,4-bonds are also present in some dextrans
Alcaligenes faecalis	Curdlan	β-1,3-glucan
Xanthomonas campestris	Xanthan	Linear β-1,4-glucan backbone with β-mannose-1,4-β-glucuronic acid-1,2-α-mannose trisaccharide side Chain
Bacillus polymyxa	Levan	β-2,6-fructan

term exopolysaccharides (EPS) (Broadbent et al. 2003). The main examples of the applications of microbial exopolysaccharides are listed in Table 2.1.

The application of these structural features has great demand in the natural components of bacterial EPS to gain a special interest in recent years in chemistry, medicine, pharmaceuticals, and especially the food industry (Jin et al. 2004). Several functions are attributed to the bacterial EPS such as protecting bacterial cells from desiccation and the environment, antibiotics, phagocytosis, and phage attacks, and they are also believed to play a role in biofilm formation (Kumar et al. 2007b). Besides the role of EPS at the single cell level, they are widely used in the food industry as viscosifying, stabilizing, and emulsifying agents because of their unique physicochemical properties related to their structures (Dhayalan et al. 2017). Dextran, xanthan, gellan, pullulan, yeast glucan, and bacterial alginate are some examples of microbial EPS used in the food industry for decades to improve the physicochemical properties of food formulations (Sutherland 1998). There are many other examples of the technological applications of EPS in food or non-food industries. Recently, EPS also gained special interest after the recent reports showing that EPS may stimulate and modulate the immune system and they may play a role as antitumor, antiviral, anti-inflammatory, and antioxidant agents (Lepek and D'Antuono 2005; Liu et al. 2007).

2.2 Types of EPS

Microbial EPSs are classified into two groups according to their chemical composition, as either homopolysaccharides or heteropolysaccharides, and show a wide diversity in their structures. Homopolysaccharides are composed of the same sugar submits in their repeating unit structure with different linkages (Mikkelsen and Keiding 2002; Mu and Yu 2006). Homopolysaccharides can be part of the capsule layer of Gram-positive and Gram-negative bacteria such as oral *Streptococcus* spp. and *Escherichia* spp.; they can also be secreted to the environment as a slime material like the bacterial

cellulose produced by *Acetobacter* spp. One of the most important examples of the microbial homopolysaccharides is dextran produced by *Leuconostoc mesenteroides* which has been found to have a wide range of applications in medicine (Kanmani et al. 2011). Several lactic acid bacteria (LAB) also produce homopolymeric EPS which will be discussed later in this section. Heteropolysaccharides are made of repeating units which are composed of two or more types of sugar subunits, substituted sugars, and other organic and inorganic molecules (Broadbent et al. 2003; Cheng et al. 2011). A general example of microbial heteropolysaccharide is peptidoglycan, which is the main component of bacterial cell walls and is composed of the repeating units of N-acetylglucosamine and N-acetylmuramic acid residues.

The polysaccharides produced by microorganisms can be classified into three main groups according to their location in the cell: (1) cytosolic polysaccharides, which provide a carbon and energy source for the cell; (2) polysaccharides that make up the cell wall, including peptidoglycans, teichoid acids, and lipopolysaccharides; and (3) polysaccharides that are exuded into the extracellular environment in the form of capsules or biofilm known as EPSs (Freitas et al. 2012; Kalogiannis et al. 2003). Exocellular polysaccharides constantly diffused into the cell culture medium are easily isolated, while cell wall and intercellular polysaccharides are more difficult to separate from cell biomass. The intracellular biopolymers are few and have very limited use. The external cellular structure capsule has covalent bonds and cohesive layers while slime is completely excreted into the environment. Extracellular polymers are polysaccharides in more than 95% cases. Unattached EPS production is especially valuable for biotechnological industry as there is no need for costly procedures for removing cell debris.

2.3 Composition and Structure

Carbohydrates and proteins are usually found to be the major components of EPS. Humic substances may also be a key component of the EPS in sludge in biological wastewater treatment reactors, accounting for approximately 20% of the total amount. In addition, lipids, nucleic acids, uronic acids, and some inorganic components have also been found in EPS from various matrixes. Their fractions in EPS depended strongly upon the extraction methods and the sludge origins. The content and compositions of the EPS extracted from various microbial aggregates are reported to be heterogeneous (Sutherland 2001a). The variation in the compositions of the extracted EPS is attributed to many factors, such as culture, growth phase, process parameter, bioreactor type, extraction method, and analytical tool used (Fig. 2.1).

Different numbers of chemical structures of bacterial EPSs are available; in general, they are heteropolysaccharides possessing three or four different monomers organized in groups of a set of 10 or less to give the repeating units. The molecular weight of these polymers is between 1×10^5 and 3×10^5 Da and they are linear too. In addition to monosaccharides, they could possess substituents such as acetate, pyruvate, succinate, phosphate, and sulfate; the presence of uronic acids or ketal-linked pyruvate resulted in polyanionic chains. The most frequent monosaccharides found in EPSs are hexoses,

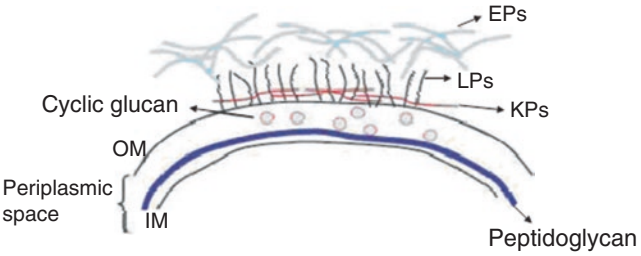

Fig. 2.1 Schematic representation of bacterial surface polysaccharides. *EPS* exopolysaccharides, *KPS* exopolysaccharides attached to the bacterial surface, *LPS* lipopolysaccharides, *IM* cell internal membrane, *OM* cell outer membrane (Lazaridou et al. 2002)

pentoses, uronic acids, and amino sugars which bind each other by 1,4-β or 1,3-β linkages in the strong rigidity polymer structure while the 1,2-α- or 1,6-α linkages are generally present in the flexible polysaccharides (Freitas et al. 2009).

The position in EPS structures is very important to explain the physicochemical and biological properties of these biopolymers and to characterize and in some case to predict the biotechnological applications of the EPS-producer microorganisms or of their bioproducts. Numerous chemical and physical techniques are used to determine the primary structure of EPSs such as chemical degradation and derivatization, in association with chromatographic methods together with mass spectrometry analysis; some are used to determine the sugar composition, their absolute configuration, and the presence and the position of possible substituents (Pan and Mei 2010). With the help of rheological properties of these polymers, the primary conformation can be easily detected. Moreover, secondary configuration regularly takes the form of aggregated helices, and the presence and the absence of specific acyl groups, for example, O-acetyl or O-succinyl esters or pyruvate ketals, can influence the formation of ordered helical aggregates.

2.4 Production of EPS

2.4.1 Conditions for Microbial Production of EPS

Fermentation is a very versatile technique for producing value-added products such as microbial EPS production. All fermentation conditions like medium composition, pH, temperature, aeration, as well as mode of operation are known to have a high impact upon the viability and economics of the bioprocess; their optimization is compulsory in designing a commercial bioprocess (Wilen et al. 2003). Moreover, structural features and related physicochemical and rheological properties of the EPS are largely determined according to the metabolic requirements of the microorganism and also by conditions of the fermentation; therefore, each microbial system should be optimized individually by avoiding generalizations. Fermentation process involves conventional methods like batch, fed-batch, and continuous modes

of operations, but in this production, drastic changes in rheological properties of the microbial culture, for example, highly viscous and non-Newtonian broth, may result in great problems in mixing, heat transfer, and oxygen supply (Palaniraj and Jayaraman 2011).

These are the challenges encountered in the microbial production of pullulan and xanthan, but are not encountered in the production of low-viscosity polymers such as levan or in high-temperature processes where thermophiles are utilized as microbial producers. Media for fermentation utilizes almost one-third of the opposed to production costs, and particularly the carbon source which is used as the fermentation feedstock has the greatest cost. Irrespective of whether the production is either at laboratory scale or large industrial scale, media with a high carbon to nitrogen ratio are used owing to the carbon-and energy-intensive nature of the process. Intended to biopolymers with high economic values, consistency in product quality relative to production yield becomes vital, which in turn needs chemically distinct medium conditions. In addition to that, recent efforts are mainly devoted to maintain both product quality and yield by using cost-effective and environmentally friendly production methods that employ inexpensive fermentation substrates (Rijnaarts et al. 1999). In consequence, a wide variety of industrial and agricultural waste and by-products are used in many industrial fermentation products like nutrients such as molasses and syrups, wastewater of olive oil pill, whey of cheese, pomade of various vegetables and fruits, pulp and kernels, lignocellulosic biomass like hall rice and bran, sawdust, and fibers (Poli et al. 2013). Utilization of such complex feedstocks requires intensive research activities for the development of feasible pretreatment, fermentation, and downstream processing techniques. From these, syrups and molasses have long been used for microbial production of various polysaccharides such as xanthan, dextran, pullulan, gellan, and levan due to their high sucrose and other nutrient contents, low cost and ready availability, and ease of storage (Morgan et al. 1990; Kalogiannis et al. 2003; Liu et al. 2004; Poli et al. 2013). Another promising resource is carbon dioxide since it is abundant, renewable, nontoxic, and non-flammable. Microalgae due to their high-CO_2 fixation capacity and fast growth served as established resources in next-generation biofuel technology. Moreover, use of microalgae in EPS production is a quite recent subject with only limited number of reports; however, controlled cultivation systems provide high yield production and also required photobioreactors that are very much expensive and energy intensive when compared with open systems (De Vuyst and Degeest 1999).

Subsequently in the microbial fermentation, the EPS is separated from the culture broth by first eliminating the cellular biomass via centrifugation or filtration. Then, the polymer in clarified medium is precipitated by using a suitable organic solvent like ethanol, acetone, or methanol. The polymer pellet can be dried by lyophilization or heat treatment of obtained crude polymer powders. For higher levels of purity, the pellet is dissolved in suitable solvent (usually water) and then either subjected to additional round of solvent precipitation or dialysis or a combination of these followed by a final drying step (Wingender et al. 1999).

2.4.2 Gene, Genetics, and Gene Expression of Regulation of Microbial Polysaccharide

The production of microbial EPS is usually not confined to just one type of EPS but a mixture of various polymers, each being expressed and produced by a certain gene cluster. Usually, the convenience of the precursors encoded by these genes has a high impact on the yield and structure of the EPS produced by the cell (Parolis et al. 1996).

As a systematic approach for biosynthetic pathways of EPS, microbial genome sequence is considered as a starting point, and from this point of view, next-generation sequencing (NGS) technologies play a vital role by enabling high-throughput genomic data at very high speed with a relatively low cost. Such approaches either aim to elucidate biosynthesis mechanisms, to improve the microbial productivity via strain improvement strategies, or to modify physicochemical and/or rheological properties of the biopolymer by changing its composition, length, or degree of branching (Toksoy Öner 2013).

Current research helps to analysis of a genus *Bifidobacterium* revealed high variability in both the number and organization of the EPS biosynthetic gene by comparative genomics, which in turn suggested that these genes were most probably acquired by horizontal transfer (Gauri et al. 2009). Comparisons of six genomes of *Crocosphaera watsonii* strains were studied with production of high-level EPS, where high-level EPS producers were found to retain the EPS biosynthesis gene clusters (Bench et al. 2013). So from the above study, the location of these gene clusters is usually on the chromosome, whereas in most LAB as well, these genes are found to be confined to plasmids.

Sequence data of a taxonomically close species could also be used for systems-based studies while the whole genome sequence of the EPS-producer microorganism is not available. Construction of metabolic model for levan production by halophilic strain *Halomonas* spp., where first, the available whole genome sequence of a taxonomically close microorganism, *Chromohalobacter salexigens* After it was used (Ateş et al. 2013), as a model for recruitatin and adoptation to the producer strain via integration of the available biochemical, physiological, and phenotypic features of *Halomonas* spp. With metabolic system analysis of this generic metabolic model, significant improvement in levan yields was obtained (Ateş et al. 2011).

EPS Application in Wastewater Treatment

EPSs cover the surface or fill in the interior of cells of microbial aggregates during wastewater treatment of vessels. Li and Ganczarczyk (1990) noted that in the interior of activated sludge flocs with amorphous-phase surrounding cells, the presence of plenty of EPS was observed (Li and Ganczarczyk 1990). This recommends that substrate must pass through the EPS layer for proper biochemical processes to the cells. The substrate efficiency is affected by many factors, viz., mass transfer, pores in granular sludge, and chemical nature of EPS (Liao et al. 2001; Vanhaverbeke et al. 2003). Normally, water has high component diffusion coefficients compared

to EPS, which means that EPS may provoked the import of nutrients and the export of metabolic products; as impermeable substances, EPS may prohibit the permeation of dye to cells. EPSs significantly influence the effective diffusion coefficients of substrates; a high level of EPS is not beneficial for substrate mass transfer (Küçükaşık et al. 2011). The permeability of anaerobic granules was found to be lower at a higher level of EPS (Li and Ganczarczyk 1990). However, as EPS can adsorb organic substances and increase their concentration in the region of the cell surface, the role of EPS in mass transfer must be carefully considered.

There are different charged groups in EPS; their composition and content interfere the surface ions of microbial aggregates. Moreover, the physicochemical characteristics of the various components in EPS are not studied properly till today, so they have different effects on the surface charge of aggregates. Frequently, the EPS content had a positive ionic bond on the net negative surface charge so that the total EPS content and the individual components both had a positive effect on the negative charge of sludge, which gives the effects of proteins and humic substances that are the most significant. Liao et al. (2001) reported that the carbohydrate content of EPS had a positive relationship with the net surface charge (Liao et al. 2001), whereas Wang et al. (2005) studied that changes in EPS composition and its surface characterized by sludge which may in the aerobic sludge granulation process as well found that the total EPS content and the protein and carbohydrate contents had a negative effect on the net surface charge of sludge (Vedyashkina et al. 2005). In contrast, the DNA content had no significant effect on either the surface charge or the hydrophobicity of the sludge (Lebeer et al. 2008; Sutherland 2001b).

The ratios between EPS components have a more significant effect on surface charge of microbial aggregates than the content of individual components. The proteins/carbohydrates ratio was found to have a negative effect on net surface charges of sludge, while total EPS composition was found to have no influence. This attributed to the unique charge properties of proteins. The amino groups in proteins are positive and can neutralize the negative charges from carboxyl and phosphate groups and thus decrease the net negative surface charges of sludge.

The role of EPS component in relation to flocculation has also been studied; the microbial aggregates have a tendency to deflocculate after the removal of their surface proteins. However, addition of a small amount of protein-hydrolyzing enzyme to a reactor would lead to the sludge de-flocculation, while dose of a carbohydrate-degrading enzyme caused much less de-flocculation. Nucleic acids may also play an important role in flocculation where bacterial flocculation ability worsened after the degradation of nucleic acids in the EPS of *Rhodovulum* sp., which was treated by nucleic acid hydrolase. Wilen et al. (2003) observed that the flocculation ability of sludge was proportionate with the protein content or adversely proportionate with the humic substance content (Wang et al. 2008). Thus, the production implies that the influence of individual EPS components on the flocculation of microbial aggregates is complex. The ratios of the main EPS components may be more influential on the microbial flocculation (Lebeer et al. 2008). The researchers also observed that readily extracted EPSs are more beneficial for flocculation. In year 2007, Li and Yang observed that the LB-EPS had a negative effect on sludge flocculation and

excessive EPS in the form of LB-EPS could weaken cell attachment and result in poor flocculation (Liu et al. 2004).

The theory of microbial cell flocculation can be described using the classical Derjaguin–Landau–Verwey–Overbeek (DLVO) or its extended theories. In the DLVO theory, the total energy of adhesion is the result of the van der Waals attractive forces and the generally repulsive interactions due to the interpenetration of the electrical double layers (Parolis et al. 1999), while the van der Waals forces, polar interactions, electrical double layer interaction, and Brownian movement forces are taken into consideration by the extended DLVO theory. The cell could aggregate and flocculation would occur; the cell kinetics may lead to overcome the total energy barrier in the DLVO curves. This theory also provides an effective way to evaluate the contribution of EPS to production as well as to the sludge flocculation.

EPS can be regarded as key factors in the thickening and dewatering processes of sludge (Hellerqvist and Sweetman 1990; Li and Ganczarczyk 1990). There are major two types of binding mechanisms between water molecules and EPS that are involved: (i) electrostatic interactions and (ii) hydrogen bonds. The electrostatic interactions are active between the permanent functional dipole group of water of the EPS, while hydrogen bonds are active between EPS hydroxyl groups and water molecules. Usually, the pressure filtration is the main means for sludge dewatering. While the specific resistance to or capillary suction time is commonly used to characterize the dewatering ability of sludge through press. An increase in EPS generally leads to a poorer sludge dewatering ability, possibly because the steric force that is generated by EPS prevents contact between cells.

Flocculation in industrial waste due to macromolecules involved in EPS production, when retention of much water in sludge that increase the amount flocs in it. EPSs also have the ability to form a stable gel that prevents water seepage from the pores of flocs, which deteriorates the dewatering ability of sludge, and after the removal of EPS, the sludge dewatering ability would be improved (Chowdhury et al. 2015). However, some studies have shown that sludge dewatering ability improves as the EPS content increases (Li and Ganczarczyk 1990; Houghton and Stephenson 2002). With a higher EPS content, activated sludge had a lower shear sensitivity and lower degree of dispersion, leading to a good dewatering ability. In 2001, Houghton et al. suggested that the content of EPS in sludge had an impact on the dewatering ability of sludge (Houghton et al. 2001). Equally, as the EPS content further increased and exceeded a certain threshold, the water that was retained by the EPS significantly increased, which resulted in a lower sludge dewatering ability (Hidalgo-Cantabrana et al. 2014).

2.4.3 Silver Nanoparticles in EPS Coating

The improved experiments of degradation with our nano-catalysts on EPS coating can be attributed to the following reasons: (i) high surface area of the EPS can adsorb azo dyes; (ii) NaBH4 is expected to act as hydride source, and the AgNPs

catalysts are expected to activate the azo nitrogen bond and also to bind with the sulfur and oxygen atoms of the dyes resulting in weakening of azo double bond via conjugation; (iii) large number of oxygen atoms of the EPS could assist in increasing the number of AgNPs; and (iv) EPS networks containing more of hetero atoms are expected to exhibit hydrophilic interactions with azo dyes, which helps in bringing the dye molecules near the catalytic sites.

Progress in nanoscale sciences may provide solution to many of the current problems involving water quality. The use of nanosorbents, nanocatalysts, bioactive nanoparticles, nanostructured catalytic membranes, and nanoparticle enhanced filtration products and processes resulting from the development of nanotechnology would greatly help to get potable drinking water. Innovations in the development of novel technologies to desalinate water are among the most exciting and promising. The development of novel nanoscale materials and processes for treatment of surface water, ground water, and industrial wastewater contaminated by toxic metal ions, radionuclides, organic and inorganic solutes like pesticides, bacteria, and viruses would be the major environmental contribution of nanotechnology.

Recent studies prove that many of the issues involving potable water quality could be resolved using nanoparticles, nanofiltration, or other nano-materials. Innovative use of nanoparticles for treatment of industrial wastewater is another potentially useful application of nano-materials as many industries generate large amounts of wastewater contaminated with toxic and non-biodegradable effluents. Removal of contaminants and recycling of the contaminated water would provide significant reductions in cost, time, and labor for the industries and increase their eco-friendliness.

2.5 Conclusion

In current era of biotechnology, the application of EPS producing microorganisms in the remediation of environmental effluents is very useful. Biofilm-mediated bioremediation has been found to be a more powerful alternative to bio-remediation with planktonic bacteria as cells growing within a biofilm have greater probabilities of adaptation to various environmental conditions and their subsequent survival. For most industrial advantageous production of biofilms, optimal chemical and physiological conditions, localized solute concentrations and redox potential, allowing cells to improve mineralization processes (Chen et al. 2001). Usually hydrocarbon used in biofilm reactors, heavy metals and large volumes of dilute aqueous solutions such as industrial and municipal wastewater. The probable role of EPS in the removal of heavy metals from the environment is due to their participation in flocculation and aptitude to bind metal ions from keys. A major group of bacteria which are usually found in metal-contaminated wastewaters is sulfate-reducing bacteria (SRB). This group of bacteria has been shown to be extremely efficient in anaerobic degradation of many organic pollutants as well as in the precipitation of heavy metals from wastewater. Other bacteria exhibiting bio-sorption of toxic heavy metals in bioremediation processes include *Enterobacter* and *Pseudomonas* species.

Therefore, the search for greener technologies will probably augment the use of bacterial exopolysaccharide for industrial applications. Thus, the use of bacteria as renewable resource for the production of biopolymers can be greatly advantageous. The current knowledge about bacterial EPS advises that these polymers may cover a broad range of complex chemical structures and consequently diverse properties. Moreover, it is reasonable to anticipate that exopolysaccharides from newer bacteria would provide ample occasions for newer industrial avenues and have chattels different from those already available.

References

Ateş Ö, Toksoy Öner E, Arga KY (2011) Genome-scale reconstruction of metabolic network for a halophilic extremophile, Chromohalobacter salexigens DSM 3043. BMC Syst Biol 5:12

Ateş Ö, Arga KY, Toksoy Öner E (2013) The stimulatory effect of mannitol on Levan biosynthesis: lessons from metabolic systems analysis of Halomonas smyrnensis AAD6(T). Biotechnol Prog 29:1386–1397

Banik RM, Santhiagu A, Upadhyay SN (2007) Optimization of nutrients for gellan gum production by Sphingomonas paucimobilis ATCC-31461 in molasses based medium using response surface methodology. Bioresour Technol 98:792–797

Bench SR, Heller P, Frank I, Arciniega M, Shilova IN, Zehr JP (2013) Whole genome comparison of six Crocosphaera watsonii strains with differing phenotypes. J Phycol 49:786–801

Broadbent JR et al (2003) Biochemistry, genetics, and applications of exopolysaccharide production in Streptococcus thermophilus: a review. J Dairy Sci 86(2):407–423

Chen Y, Yang H, Gu G (2001) Effect of acid and surfactant treatment on activated sludge dewatering and settling. Water Res 35:2615

Cheng KC, Demirci A, Catchmark JM (2011) Pullulan: biosynthesis, production, and applications. Appl Microbiol Biotechnol 92:29–44

Chowdhury IH, Ghosh S, Roy M, Naskar MK (2015) Green synthesis of water-dispersible silver nanoparticles at room temperature using green *carambola* (star fruit) extract. J Sol-Gel Sci Technol 73:199–207

De Vuyst L, Degeest B (1999) Heteropolysaccharides from lactic acid bacteria. FEMS Microbiol Rev 23(2):153–177

Dhayalan M, Denison MIJ, Jegadeeshwari AL, Krishnan K, Gandhi NN (2017) In vitro antioxidant, antimicrobial, cytotoxic potential of gold and silver nanoparticles prepared using *Embelia ribes*. Nat Prod Res 31:465–468

Freitas F, Alves VD, Pais J, Costa N, Olivera C, Mafra L et al (2009) Characterization of an extracellular polysaccharide produced by a pseudomonas strain grown on glycerol. Bioresour Technol 100:859–865

Freitas AC, Rodrigues D, Rocha-Santos TAP, Gomes AMP, Duarte AC (2012) Marine biotechnology advances towards applications in new functional foods. Biotechnol Adv 30:1506–1515

Gauri SS et al (2009) Enhanced production and partial characterization of an extracellular polysaccharide from newly isolated Azotobacter sp. SSB81. Bioresour Technol 100(18):4240–4243

Hellerqvist CG, Sweetman BJ (1990) Mass spectrometry of carbohydrates. In: Smelter CH, Throck Watson J (eds) Methods of biochemical analysis. Wiley-Interscience, Hoboken, NJ, pp 91–143

Hidalgo-Cantabrana C, Sánchez B, Milani C, Ventura M, Margolles A, Ruas-Madiedo P (2014) Exopolysaccharide biosynthesis in Bifidobacterium spp.: biological functions and a genomic overview. Appl Environ Microbiol 80:9–18

Houghton JI, Stephenson T (2002) Effect of influent organic content on digested sludge extracellular polymer content and dewaterability. Water Res 36:3620–3628

Houghton J, Quarmby J, Stephenson T (2001) Municipal wastewater sludge dewaterability and the presence of microbial extracellular polymer. Water Sci Technol 44(2):373–379

Jin B, Wilen BM, Lant P (2004) Impacts of morphological, physical and chemical properties of sludge flocs on dewaterability of activated sludge. Chem Eng J 98:115–126

Kalogiannis S, Iakovidou G, Liakopoulou-Kyriakides M, Kyriakidis DA, Skaracis GN (2003) Optimization of xanthan gum production by Xanthomonas campestris grown in molasses. Process Biochem 39:249–256

Kanmani P et al (2011) Production and purification of a novel exopolysaccharide from lactic acid bacterium Streptococcus phocae PI80 and its functional characteristics activity in vitro. Bioresour Technol 102(7):4827–4833

Küçükaşık F, Kazak H, Güney D, Finore I, Poli A, Yenigün O et al (2011) Molasses as fermentation substrate for levan production by Halomonas sp. Appl Microbiol Biotechnol 89:1729–1740

Kumar AS, Mody K, Jha B (2007a) Bacterial exopolysaccharides – a perception. J Basic Microbiol 47:103–117

Kumar AS, Mody K, Jha B (2007b) Bacterial exopolysaccharides--a perception. J Basic Microbiol 47(2):103–117

Lazaridou A, Biliaderis CG, Roukas T, Izydorczyk M (2002) Production and characterization of pullulan from beet molasses using a nonpigmented strain of Aureobasidium pullulans in batch culture. Appl Biochem Biotechnol 97:1–22

Lebeer S, Vanderleyden J, De Keersmaecker SC (2008) Genes and molecules of lactobacilli supporting probiotic action. Microbiol Mol Biol Rev 72(4):728–764

Lepek CV, D'Antuono A (2005) Bacterial surface polysaccharides and their role in the rhizobia-legume association. Lotus Newslett 35:93–105. (For figure-1)

Li DH, Ganczarczyk JJ (1990) Structure of activated sludge flocs. Biotechnol Bioeng 35:57–65

Liao BQ, Allen DG, Droppo IG, Leppard GG, Liss SN (2001) Surface properties of sludge and their role in bioflocculation and settleability. Water Res 35:339–350

Liu YQ, Liu Y, Tay JH (2004) The effects of extracellular polymeric substances on the formation and stability of biogranules. Appl Microbiol Biotechnol 65:143–148

Liu Y, Yang CH, Li J (2007) Influence of EPS on Pseudomonas aeruginosa transport and deposition profiles in porous media. Environ Sci Technol 41:198–205

Manjamadha VP, Muthukumar K (2016) Ultrasound assisted synthesis of silver nanoparticles using weed plant. Bioprocess Biosyst Eng 39:401–411

Mikkelsen LH, Keiding K (2002) Physico-chemical characteristics of full scale sewage sludges with implication to dewatering. Water Res 36:2451–2462

Morgan JW, Forster CF, Evison LM (1990) A comparative study of the nature of biopolymers extracted from anaerobic and activated smudges. Water Res 6:743–750

Mu Y, Yu HQ (2006) Biological hydrogen production in a UASB reactor with granules. I:physicochemical characteristics of hydrogen-producing granules. Biotechnol Bioeng 94:980–987

Palaniraj A, Jayaraman V (2011) Production, recovery and applications of xanthan gum by Xanthomonas campestris. J Food Eng 106:1–12

Pan D, Mei X (2010) Antioxidant activity of an exopolysaccharide purified from Lactococcus lactis subsp. lactis 12. Carbohydr Polym 80(3):908–914

Parolis H, Parolis LAS, Boan IF, Rodrıguez-Valera F, Widmalm G, Manca MC et al (1996) The structure of the exopolysaccharide produced by the halophilic archaeon Haloferax mediterranei strain R4 (ATCC 33500). Carbohydr Res 295:147–156

Parolis LAS, Parolis H, Paramonov NA, Boan IF, Anton J, Rodrıguez-Valera F (1999) Structural studies on the acidic exopolysaccharide from Haloferax denitrificans ATCC 35960. Carbohydr Res 319:133–140

Poli A, Kazak H, Gürleyendag B, Tommonaro G, Pieretti G, Toksoy Öner E et al (2009) High level synthesis of Levan by a novel Halomonas species growing on defined media. Carbohydr Polym 78:651–657

Poli A, Nicolaus B, Denizci AA, Yavuzturk B, Kazan D (2013) Halomonas smyrnensis sp. nov., a moderately halophilic, exopolysaccharide-producing bacterium from Camalti Saltern area, Turkey. Int J Syst Evol Microbiol 63:10–18

Reichhardt C, Cegelski L (2014) Solid-state NMR for bacterial biofilms. Mol Phys An Int J at Interface Between Chem Phys 112:887–894

Rijnaarts HHM, Norde W, Lyklema J, Zehnder AJB (1999) DLVO and steric contributions to bacterial deposition in media of different ionic strengths. Colloids Surf B: Biointerfaces 14:179–195

Sutherland IW (1998) Novel and established applications of microbial polysaccharide. Trends Biotechnol 16:41–46

Sutherland IW (2001a) Biofilm exopolysaccharides: a strong and sticky framework. Microbiology-SGM 147:3–9

Sutherland IW (2001b) Microbial polysaccharides from gram-negative bacteria. Int Dairy J 11:663–674

Toksoy Öner E (2013) Microbial production of extracellular polysaccharides from biomass. In: Feng Z (ed) Pretreatment techniques for biofuels and biorefineries. Springer, Berlin, pp 35–56

Vanhaverbeke C, Heyraud A, Mazeau K (2003) Conformational analysis of the exopolysaccharide from Burkholderia caribensis strain MWAP71: impact of the interaction with soils. Biopolymers 69:480–497

Vedyashkina TA, Revin VV, Gogotov IN (2005) Optimizing the conditions of dextran synthesis by the bacterium Leuconostoc mesenteroides grown in a molasses-containing medium. Appl Biochem Microbiol 41:361–364

Wang Y et al (2008) Physicochemical properties of exopolysaccharide produced by Lactobacillus kefiranofaciens ZW3 isolated from Tibet kefir. Int J Biol Macromol 43(3):283–288

Wilen BM, Jin B, Lant P (2003) The influence of key chemical constituents in activated sludge on surface and flocculation properties. Water Res 37:2127–2139

Wingender J, Neu TR, Flemming HC (1999) What are bacterial extracellular polymeric substances? In: Wingender J, Neu TR, Flemming HC (eds) Microbial extracellular polymeric substances: characterization, structures and function. Springer, Berlin/Heidelberg, pp 1–18