



Microbial Polysaccharides in Food Industry: Production, Applications, Legislative and Toxicological Affairs

Tanveer Singh ^a and Reshu Rajput ^{a*}

^a University Institute of Agriculture Science, Chandigarh University, Mohali 140413, Punjab, India.

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Article Information

DOI: <https://doi.org/10.9734/cjast/2024/v43i114453>

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here:

<https://www.sdiarticle5.com/review-history/125905>

Review Article

Received: 03/09/2024

Accepted: 06/11/2024

Published: 20/11/2024

ABSTRACT

Microbial polysaccharides, including exopolysaccharides (EPS) play significant roles in various industries due to their functional properties. This review discusses the extraction and purification techniques of microbial polysaccharides from bacteria, emphasizing centrifugation, ultracentrifugation, heat treatment and specific chemical treatments based on the polysaccharide's association with cells. Techniques vary depending on whether the polysaccharides are capsular or slime forming. Notable microbial polysaccharides such as dextran, curdlan, xanthan, alginic acid, bacterial cellulose, levan and algal polysaccharides highlighted, detailing their sources, applications, and benefits in food production, stabilization, and thickening. The diverse application of these polysaccharides underlines their importance in food technology and other industries, their potential for innovation in product formulation and quality enhancement.

*Corresponding author: E-mail: reshu.rajput21@gmail.com

Cite as: Singh, Tanveer, and Reshu Rajput. 2024. "Microbial Polysaccharides in Food Industry: Production, Applications, Legislative and Toxicological Affairs". *Current Journal of Applied Science and Technology* 43 (11):167-76. <https://doi.org/10.9734/cjast/2024/v43i114453>.

Keywords: Polysaccharides; medical applications; cellulose; glycosaminoglycans.

1. INTRODUCTION

Numerous creatures, including plants, animals, and microbes, receive polysaccharides from the vast array of polysaccharides found in nature. Numerous biological processes rely on polysaccharides, including cellulose for cell walls, starch for energy storage, and glycosaminoglycans for cellular communication (Ates, 2015; Salimi, & Farrokh, 2023). Polysaccharides are widely present in nature because they are essential components of cell structure. Polysaccharides are long chains of carbohydrate molecules, composed of several smaller monosaccharides. Glycosidic linkages bind the linear or branching polymers of monosaccharides together. These polymers can either be heteropolymers, where all the monosaccharide units vary, or homopolymers, where all the monosaccharide units are same. The wide range of properties shown by polysaccharides explained by the variations in their molecular weight, type of monosaccharide units and their linkages, and the presence of substituents like amino or carboxyl groups on the monosaccharide units Salimi, & Farrokh, (2023). Many of them used in food industries and human diet, as natural ingredient or as purified food additive obtained from the fermentation of microbial polysaccharides (use of yeast), as well as pharmaceuticals (as bioactive compound or media for encapsulation), cosmetics and other industries applications (Sutherland, 1998). Microbial polysaccharides are used for food, pharmaceutical, and medical applications this wide range of usefulness derives from the great diversity in structural and functional properties. Microbial polysaccharides have several advantages as compared to synthetic and plant polysaccharides and some of them are:

Production of microbial polysaccharides are independent on regional and climatic conditions, and polysaccharide obtaining from microorganisms is effortless process. Microorganisms exhibits high growth rate, and condition optimization for growth. Microorganisms is genetically modified to produce polysaccharide with desired properties. The ingredients are simple and safe to use, required for microbial growth. Efforts have been made to use certain industrial food wastes as growth medium for microorganisms, which is not only a cheap way but also works as a basis for environmental cleaning (Ladtrat et al., 2014).

While seaweed and plants account for most of the polysaccharides used in the industry today, microbial polysaccharides with new and distinct physical characteristics have lately become significant biopolymers. Polysaccharides of microbial origin have proved themselves as new polymeric materials that are competing economically with other natural gums, such as Arabic gum and carrageenan produced by plants and marine algae, respectively (Milani and Maleki, 2012).

The microorganisms may produce a quite good quantity of polysaccharides when a plentiful carbon source is available. Glycogen is one of these polysaccharides that functions as a storing substance. Cells release polysaccharides called exopolysaccharides, which are important to the world economy. The medium may include exopolysaccharides by itself or in combination with the cells. The microbial polysaccharides might be neutral (dextran, scleroglucan) or acidic (xanthan, gellan). Acidic polysaccharides that include ionized groups, such as carboxyl, and may function as polyelectrolytes are becoming increasingly important in the market. Microbial polysaccharides have properties such as viscosity thickeners, gelling and film forming agents, stabilizer, texturizers and emulsifiers, thus have board spectrum of its application.

In recent research it is found out that some microbial polysaccharides shows significant immunomodulating properties (antitumor, anti-inflammatory, antimicrobial) thus making it essential ingredient in human diet (Giavasis and Biliaderis, 2006).

For particular groups of consumers, the applications of animal-based-gelatin in the food and pharmaceutical products are restricted because the animal source does not meet their religions' requirement. Muslims and Jews are prohibited to consume any pork related products, Hindus are not allowed to consume beef, while vegetarians and vegans do not include any meat in their diet. The outbreak of mad cow disease in the 1980s is another concern for consumers due to the risk of consuming gelatin from infected cattle. Food processors are already seeking substitutes for animal-sourced ingredients. Although these alternatives meet some gelatin characteristics, none is yet available that matches all the desired functional properties of gelatin. Until now macromolecules of plant origin include starch, locust bean gum, guar gum,

carrageenan, and alginate, have captured the commercial market for their ease of availability and cost-effective purification process. However, renewability, stable cost, constant, and reproducible physio chemical properties of the microbial polysaccharides have provided them an edge over the macromolecules of plant origin, although so far only few of them have been commercialized. One limitation is polysaccharide-based gels generally lack molecular backbones flexibility which tend to have higher viscosities compared to animal-based gelatin.

2. EXTRACTION AND PURIFICATION OF MICROBIAL POLYSACCHARIDES

Various techniques are utilized to extract distinct types of exopolysaccharides from bacteria. Centrifugation is often used to remove EPS that has slime forms. The kind and viscosity of the polysaccharides determine centrifugation duration and spread. Ultracentrifugation can be used to extract microbial biomass or their waste products from the growth medium for improved outcomes in the lab (Singha, 2012). Heat treatment can be utilized to enhance the separation of microorganisms from the broth

when the EPS is thermally stable. The heat treatment inactivates the enzymes in the culture broth and kills the cell by pasteurization, but it has no effect on the viscosity of these polysaccharides (Bajaj et al., 2007; Singha, 2012). Because the capsular EPS must first be separated from the cells, the extraction of capsular polysaccharide is somewhat different (Sanchez et al., 2006; Sreekanth et al., 2013; Vijayendra and Shamala, 2014). The kind of interaction between the polysaccharide to be extracted and the cell determines the procedures for separation and purification used for capsular polysaccharides. Centrifugation is used to accomplish separation when the capsular extracellular polymeric substances (EPS) have a poor association with bacteria (Sutherland, 1990). When the capsular EPS is tightly associated with the cells, more severe treatments (such as alkaline treatment or treatment with sodium chloride, EDTA, and alcohol precipitation) are performed prior to centrifugation. Beside chemical treatments, the other methods include boiling the microbial cell suspensions for 15 min, heating at 60°C in saline solution, heating in a mixture of phenol and water at 65°C, or sonicating the cell suspension (Khoddami et al., 2013).

Table 1. Some microbial polysaccharides, their source and application

Microbial polysaccharide	Source	Uses or application	References
Dextran	Leuconostocmesenteroides, lactobacillus sps.	Thickener agent (ice cream), improving bread quality (softness texture).	(Wüstenberg, 2015).
Curdlan	Agrobacterium sps	Stabilizer, thickener, texturizer (tofu, noodles, meat, jellies).	(khan et al., 2007).
Xanthan	Xanthomonas compestris	Gluten free baking, thickening and stabilizing (sauces, soups, etc.).	(Abarquero et al., 2022).
Alginic acid	Pseudomonas aeruginosa and Azotobacter vinelandii	Thickener (sauces, syrups, ice cream), gelling, stabilizing, etc.	(Guo, et al., 2020).
Bacterial cellulose	Acetobacter, Achromobacter, Rhizobium	Food additive, food packaging, low calorie food, etc.	(Ul-Islam et al., 2019).
Levan polysaccharides	Corynebacterium levaniformans, Aspergillus sydowii,	Sweetener and fiber (dairy products), thickener, emulsifier, stabilizer, etc.	(Yu et al., 2017).
Exopolysaccharides	Lactic acid bacteria, endophytic fungi	Thickener and stabilizer (dairy products), texture (meat products), etc.	(Abarquero et al., 2022).
Algal polysaccharides	Microalgae and cyanobacteria	Thickening, gelling, emulsifying, packaging, etc.	(Pateiro et al., 2021).

3. DEXTRAN

The first microbial polysaccharide to be approved for use in food. Dextran is produced by fermentation of sucrose by means of enzymes of *Leuconostoc* or *Streptococcus* at pH 6.5 to 7. When organic solvents like methanol, ethanol, etc. are added, dextrans are precipitated. By precipitation, all unwanted contaminants are removed and resulting with white powder (Wüstenberg, 2015). Dextran is produced in an extracellular process by fermentation of sucrose by enzymes of *Leuconostoc* or *Streptococcus* at pH 6.5–7. After fermentation, the culture medium is cleared of microorganisms. The solubilized dextrans are precipitated by the addition of organic solvents, such as methanol, ethanol, 2-propanol, or acetone. By reprecipitation, entrained contaminants are removed. The resulting product is a white powder (Wüstenberg, 2015). Dextran is highly branched, neutral homopolysaccharide made up of glucose unit. At room temperature, dextran is readily soluble in water. Dextran forms highly viscous and slimy liquids (Kapoor et al., 2013; Yu et al., 2017).

3.1 Applications

Dextran is added in baking industry to bake goods to enhance softness, crumb texture, and loaf volume. It is used as stabilizer in confections to help with moisture retention, taste preservation, viscosity, and prevention of crystallization. It is also utilized in soft drinks, milk beverages, and icing composition. Dextran is thought to offer benefits over other stabilizers since it is tasteless, odorless, and nontoxic (Bhavani and Nisha, 2010) (Kothari et al., 2014).

3.2 Legislative and Toxicology Affairs

Because dextran is easily broken down in the digestive system of humans, it may be used as an energy source. Since it expands blood plasma, the kidneys can readily get rid of it. Thus, it has approval in many countries for use in food products. There is no acceptable daily intake value mentioned for dextran.

4. CURDLAN

A fermentation produced polysaccharide that is a member of the glucans class of molecules. Curdlan is produced in an extracellular process by the nonpathogenic bacterium *Agrobacterium biovar* and mutants of *Alcaligenes faecalis*. The powder is colorless and odorless (Zhang and

Edgar, 2014). Glucan is mainly insoluble in water below 54°C. Above this point, heating the solution causes it to swell and solidify into a strong, elastic gel. Gel strength is in the range of gelatin and agar. Aqueous alkaline solution can dissolve curdlan (Saha and Bhattacharya, 2010 and Tomasik, 2004).

4.1 Physical Properties

Heating causes curdlan to form an irreversible gel. The gel becomes stronger as the temperature rises. The curdlan produces insoluble films in water. These gels are edible, biodegradable, and oxygen impermeable (Ghanbarzadeh and Almasi, 2013; Khan et al., 2007).

4.2 Applications

Curdlan finds application in the food and pharmaceutical sectors as a gelling agent. Gelatin and agar is replaced by curdlan for making jellies, sweets, and confectionary. Additionally, dietetic meals (such as salad dressings, desserts, and pasta) employ it as a thickening and binder. To extend the shelf life of food goods, it is also used as an edible coating (Nishinari et al., 2009).

4.3 Legislative and Toxicology Affairs

The US FDA has authorized curdlan as a food ingredient. Curdlan has also been licensed for use in food in Japan (Shetty et al., 2006; Venugopal, 2011).

5 XANTHAN GUM

A microbial polysaccharide produced by the bacterium *Xanthomonas campestris* that is often used in foods for people with dysphagia. The 1960s saw the discovery of xanthan gum, which became commercially available in the 1970s (Wüstenberg, 2015). It is made by using pure cultures of *Xanthomonas campestris* to ferment glucose or sucrose solution aerobically. Following the inoculation of a chosen bacterial strain, fermentation is continually carried out for around three days at 30°C. Sterilization is done on the broth after fermentation is finished in order to get rid of any living microorganisms. Centrifugation is the method used to remove the extracellular components. Isopropyl alcohol precipitation is used to recover xanthan. Xanthan fibers are separated using centrifugation or filtering, and then they are dried and ground for

packing. About 50000 MT of xanthan gum are produced annually worldwide, with 50% of that amount going toward culinary applications. A marketed white xanthan powder has an approximate moisture content of 11% and an ash content of 6% to 9% (Nwokocha, & Williams, (2020).

5.1 Chemical Composition and Structure

Xanthan is long chain polysaccharide having large number of trisaccharide side chain and a molecular ratio 3:3:2, d-glucose, d-mannose, and d-glucuronic acid make up the building blocks of xanthan. The average molecular weight of the xanthan is 2000kDa.

5.2 Physical Properties

Xanthan gum is a fast-hydrating water-soluble hydrocolloid that can easily be dissolved at room temperature. Continuous mixing and stirring reduce the hydration time of xanthan. Long-chain xanthan polymers are easier to disperse but slow to hydrate. Generally, hydration depends on the ionic strength. If there is high ionic strength, the hydration tends to be slow. With increase in temperature, the otherwise rigid ordered state at low temperature turns to a more flexible, disordered state, and conformational transition of the solution occurs. Xanthan solutions have the viscoelastic properties forming a weak gel, giving suspending characteristics in liquid foods, such as dressings, sauces, or cakes before baking. The behavior of xanthan solutions does not change over a wide range of pH (3–10). It is reported that it is more stable than other thickeners and even resistant to enzymes, such as amylases, proteases, and cellulases (Wüstenberg, 2015).

5.3 Applications

The main use of xanthan is in dressings and sauces. Addition of xanthan in dairy desserts supports gel formation and reduces syneresis (Saha and Bhattacharya, 2010).

6. ALGINIC ACID

An edible polysaccharide found in brown algae that is also known as algin. Alginic acid is commonly used natural polysaccharide that is obtained from brown seaweeds such as macroalgae, kelp, gulfweed, and *Ascophyllum*. It can also be produced by microbial fermentation

using specialized bacteria (Aderhold, D., et al. 1996). The cytoplasm contains alginic acid by nature, which is important for strengthening the cell wall (A° gren, M. S. (1996). According to Myklestad research, alginic acid is mostly contained in cell as calcium alginate, but it is also partially present as magnesium alginate, potassium alginate, and sodium alginate. The extract obtained from seaweeds is usually sodium alginate.

6.1 Physical properties

Thick colloid is formed when sodium alginate is dissolved in water and its volume can increase with respect to the water absorption. Sodium alginate solution has anti charge because it maintains negative ion group and condenses hydrophobic suspension (Guo, X., et al. 2020). Alginic acid has antianaphylaxis effect, immunomodulatory activity, antioxidant activity, and anti-inflammatory effect.

6.2 Legislative and Toxicology Affairs

Sodium alginate is an indispensable nutrient for the human body-edible fiber (Guo,X et al., 2020). It has an auxiliary curative effect on the prevention of colon cancer, cardiovascular disease, obesity, and the accumulation of lead and cadmium in the body. Sodium alginate is known as “health and longevity food” in Japan and is a wonderful food additive in the United States (Aderhold et al., 1996). As a species of seaweed gum, it can improve the properties and structure of food with its inherent physical and chemical improvement.

7. BACTERIAL CELLULOSES

A microbial polysaccharide that can form various shapes and textures and can change the flavor and color of food. Bacterial cellulose is produced by various bacterial species. Well known examples are *Salmonella*, *Acetobacter*, *Rhizobium*, *Agrobacterium*, *Aerobacter*, *Azotobactoe*, *Sarcina ventriculi*, and *Glucanacetobactor* (Ullah MW, et al. 2017). Inside the bacterial cell, β -1,4glucan chains are formed, which are the precursors of bacterial cellulose. The terminal complexes, which are located at the cell's outer membrane, allow the polymers to be expelled into the culture medium. These polymers crystallize in the medium to form highly organized structures including protofibrils, ribbons, and bundles, which are ultimately transformed into hydrogels at the medium air

contact (Kim Y, et al. 2019). Bacterial cellulose performs several functions that are important for the life cycle of the organisms. These include flocculation and plant attachment facilitation. When compared to cellulose derived from plants, bacterial cellulose has several unique characteristics that set it apart, including high purity, hydrophilic nature, and a finer three-dimensional fiber structure (Ul-Islam M, et al. 2019).

8. LEVAN POLYSACCHARIDE

It is naturally occurring polysaccharide found in many plants and microorganisms. Many plants and microbes naturally contain levan, a fructan (Meyer, Diederick 2015). This polymer is composed up from fructose, a monosaccharide sugar, joined by 2,6 beta glycosidic links. Levan may have comparatively low molecular weight structures that are both branching and linear (Gehatia, M & Feingold, D. S. 1957). With basal chains that are nine units long, branched levan produces a very tiny, sphere-like structure (Arvidson et al., 2006). The spherical shape of methyl ethers is produced by the 2,1 branching. Levan also typically has a glucosyl residue at the ends (Srikanth et al., 2015). Compared to linear polysaccharides, branching levan is often more stable (Öner et al., 2016). Nonetheless, there is often variation in the duration of polymerization and degree of branching between species (Srikanth et al., 2015). 6-kestose, a chain consisting of two fructose molecules and a terminal glucose molecule, is the shortest levan.

8.1 Production

A few plants species, bacteria, fungus, and archaea all manufacture levan. Sucrose, a disaccharide including glucose and fructose, is the starting point for the synthesis of fructans like levan (Öner et al., 2016). Levan is also formed by bacteria using fructosyltransferase called levansucrase (Öner et al., 2016). In order for branching sites to occur, these bacterial enzymes create the 2,1 connections in the linear basal chains of levan. Levan is produced externally by several microorganisms (Öner et al., 2016). A number of variables, including pH, oxygen content, and temperature, may have an impact on its formation (Öner et al., 2016). Levan production in bacteria is usually indicative of population expansion. Soybean mucilage may also be produced by breaking it apart. Microbes create levans when they colonize a food substrate. Levan and amylovoran are released

by *Erwinia amylovora* as a component of its biofilm. When combined, they add to its pathogenic potential (Mansfield et al., 2012). A sourdough technique with significant levan production (among other exopolysaccharides) was developed in 2016 (Sutherland, (2001).

Levan's beta 2,6 connections make it soluble in both water and oil, albeit the amount of solubility varies depending on the water's temperature (Ouweland, Arthur 2012). Levan is also insoluble in a wide range of organic solvents, including isopropanol, methanol, and ethanol. Levan's strong cohesive and tensile strength is a result of its branching, and its hydroxyl groups help it stick to other molecules (Srikanth et al., 2015). Levan typically has a relatively low intrinsic viscosity η , which is a measure of the substance's impact on a solution's viscosity. Levan can now be used in a pharmaceutical context because to this (Ouweland, Arthur 2012).

8.2 Legislative and Toxicology Affairs

Levan is a substance used in many sectors, including food, drinks, cosmetics, and even medical. Levan complies with all safety regulations, which is one of the reasons it can be used so extensively. Levan has no have any allergic effects, does not irritate skins or eyes, and does not provide a cytotoxic risk.

9. EXOPOLYSACCHARIDES (EPS)

Polysaccharides that are synthesized by lactic acid bacteria during fermentation and have prebiotic characteristics. EPS has the ability to replace commercially available food additives since it is a natural substitute for artificial additives and has physiochemical properties. The films and coatings on fruits and vegetables that are edible are eatable and have a thickness of around 0.3 mm. To improve the preservation of processed fruits and vegetables, these coatings are frequently used (Nwokocha and Williams 2021). These films might be based on lipids, proteins, or polysaccharides. Sometimes it becomes quite difficult in the case of artificial film and coatings. Since humans directly ingest these, it is unacceptable. Thus, these coatings and films have to be entirely organic in origin. Because of this, bacterial extracellular polymerization (EPS) offers the most favorable conditions for the development of these coatings and films (Daba et al., 2021).

9.1 Applications

EPS is employed in the food business for a variety of purposes as biothickeners. Additionally, they have a few key techno-functional qualities that set them apart for application in the food sector (Ryan et al., 2015). They are also used in food packaging and guarantee creaminess, mouthfeel, and improved food texture. In addition to rheological qualities including decreased syneresis, increased viscosity, and enhanced texture, they also impart stabilizing, emulsifying, and thickening capabilities to food material (Abarquero et al., 2022).

9.2 Properties

There are multiple properties of EPS when it is used as edible films or coatings. First, they act as a barrier to gases and moisture loss. In this way, the process of oxidation and spoilage is retarded. This adds up to the shelf life of the food products. For example, gellan and xanthan gums are excellent and commonly used to attain gas and moisture barrier properties (Lynch et al., 2018). In the same way, these are widely used in food packaging as they are biodegradable. The packaging made by xanthan gums can decompose more rapidly as compared to any other artificial packaging (Kim et al., 2013).

10. ALGAL POLYSACCHARIDES

Polysaccharides that have antibacterial and anti-inflammatory properties, and are sometimes considered dietary fiber. Algal polysaccharides are renewable, abundant, biodegradable, biocompatible sources for biopolymer production and are highly used in the food industry as a thickening, gelling agents, emulsifiers, and stabilizers, and also used as packaging material (edible coating or film for active and intelligent packaging) (Scieszka&Klewicka, 2019).

10.1 Application

The increasing awareness among consumers about foods that promote health has driven the food industry to develop products with the incorporation of bioactive compounds (Karelakis et al., 2020). In this context, nanotechnology can contribute to obtaining functional foods and nutraceuticals. Nanoencapsulation of bioactive compounds for food enrichment can prevent the degradation of these compounds during processing and storage and increase stability and bioavailability, preserving their bioactivity (He

et al., 2016). Furthermore, using polysaccharides as encapsulants in the food industry can prevent the loss of volatile compounds and improve the dispersion of low-solubility compounds in the food matrix (Pateiro et al., 2021). Polysaccharides from algae have characteristics of interest as an encapsulating material, such as bioavailability, biocompatibility, bioactivity, and non-toxicity (Zavareze et al., 2019).

10.2 Legislative and Toxicology Affairs

Polysaccharides have been associated with many other significant biological activities such as anticoagulant, antithrombotic, and antiviral activities including anti-HIV infection, herpes, and hepatitis viruses, and their health benefit properties have been deeply studied. Generally, biological activities of sulfated polysaccharides are related to their different compositions and extent of sulfation (Mišurcová, L. 2011).

11. CONCLUSION

Polysaccharides play a crucial role in various biological processes and applications, serving as fundamental components in both plant and microbial systems. Their structural diversity—resulting from variations in monosaccharide composition, linkage types, and functional groups—enables a wide range of functionalities. Microbial polysaccharides, in particular, have emerged as significant alternatives to traditional plant-based polysaccharides, offering benefits such as consistent quality, rapid production, and potential for genetic modification to enhance specific properties. The applications of microbial polysaccharides span across multiple industries, including food, pharmaceuticals, and cosmetics. Their ability to act as thickeners, emulsifiers, and stabilizers, combined with unique health benefits such as immunomodulation and prebiotic effects, positions them favorably in the market, especially amid growing consumer demand for vegan and allergen-free ingredients.

Despite their advantages, challenges remain in the commercial utilization of microbial polysaccharides, primarily concerning extraction methods and the functional properties of polysaccharide gels compared to animal-derived alternatives. However, ongoing research and technological advancements hold promise for overcoming these limitations and expanding the scope of microbial polysaccharides in various applications. Overall, the future of polysaccharides, particularly those derived from

microbial sources, appears promising, as they continue to adapt to the needs of modern industries and consumer preferences for safe, effective, and sustainable ingredients.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

- Abarquero, D., Renes, E., Fresno, J. M., & Tornadajo, M. E. (2022). Study of exopolysaccharides from lactic acid bacteria and their industrial applications: A review. *International Journal of Food Science & Technology*, 57(1), 16–26.
- Aderhold, D., Williams, C. J., & Edyvean, R. G. J. (1996). The removal of heavy-metal ions by seaweeds and their derivatives. *Bioresource Technology*, 58(1), 1–6.
- Ågren, M. S. (1996). Four alginate dressings in the treatment of partial thickness wounds: A comparative experimental study. *British Journal of Plastic Surgery*, 49(2), 129–134.
- Arvidson, S. A., Rinehart, B. T., & Gadala-Maria, F. (2006). Concentration regimes of solutions of levan polysaccharide from *Bacillus* sp. *Carbohydrate Polymers*, 144–149.
- Ates, O. (2015). Systems biology of microbial exopolysaccharides production. *Frontiers in Bioengineering and Biotechnology*, 3, 200.
- Bajaj, I. B., Survase, S. A., Saudagar, P. S., & Singhal, R. S. (2007). Gellan gum: Fermentative production, downstream processing and applications. *Food Technology and Biotechnology*, 45, 341–354.
- Bhavani, A. L., & Nisha, J. (2010). Dextran—the polysaccharide with versatile uses. *International Journal of Pharmaceutical and Biological Sciences*, 1(4), 569–573.
- Daba, G. M., Elnahas, M. O., & Elkhateeb, W. A. (2021). Contributions of exopolysaccharides from lactic acid bacteria as biotechnological tools in food, pharmaceutical, and medical applications. *International Journal of Biological Macromolecules*, 173, 79–89.
- Gehatia, M., & Feingold, D. S. (1957). The structure and properties of levan, a polymer of D-fructose produced by cultures and cell-free extracts of *Aerobacter levanicum*. *Journal of Polymer Science*, 783–790.
- Ghanbarzadeh, B., & Almasi, H. (2013). Biodegradable polymers. In R. Chamy & F. Rosenkranz (Eds.), *Biodegradation: Life of science* (pp. 141–185). Intech
- Giavasasi, S. & Biliaderis, C. G. (2006). Microbial polysaccharides. In C. Biliaderis & M. Izydorczyk (Eds.), *Functional Food Carbohydrates* (pp. 167–214). CRC Press.
- Guo, X., Wang, Y., Qin, Y., Shen, P., & Peng, Q. (2020). Structures, properties and application of alginic acid: A review. *International Journal of Biological Macromolecules*, 162, 618–628.
- He, X., & Hwang, H. M. (2016). Nanotechnology in food science: Functionality, applicability, and safety assessment. *Journal of Food and Drug Analysis*, 24, 671–681.
- Kapoor, M., Khandal, D., Seshadri, G., Aggarwal, S., & Khandal, R. K. (2013). Novel hydrocolloids: Preparation & applications—a review. *International Journal of Recent Research and Applied Studies*, 16(3), 432–482.
- Karelakis, C., Zevgitis, P., Galanopoulos, K., & Mattas, K. (2020). Consumer trends and attitudes to functional foods. *Journal of International Food & Agribusiness Marketing*, 32, 266–294.
- Khan, T., Park, J. K., & Kwon, J. H. (2007). Functional biopolymers produced by biochemical technology considering applications in food engineering. *Korean Journal of Chemical Engineering*, 24, 816–826.
- Khoddami, A., Wilkes, M. A., & Roberts, T. H. (2013). Techniques for analysis of plant phenolic compounds. *Molecules*, 18, 2328–2375
- Kim, S. H., Kim, K. S., Kim, S. K., Yoon, Y. O., Cho, K. S., & Lee, K. A. (2013). Microstructure and mechanical properties of Eco-2024-T3 aluminum alloy. *Advanced Materials Research*, 602, 623–626.
- Kim, Y., Ullah, M. W., Ul-Islam, M., Khan, S., Jang, J. H., & Park, J. K. (2019). Self-assembly of bio-cellulose nanofibrils through intermediate phase in a cell-free enzyme system. *Biochemical Engineering Journal*, 142, 135–144.

- Kothari, D., Das, D., Patel, S., & Goyal, A. (2014). Dextran and food application. In K. G. Ramawat & J. M. Merillon (Eds.), *Polysaccharides* (pp. 1–16). Springer International Publishing AG
- Ladrat, C. D., Sinquin, C., Lebellenger, L., Zykwincka, A., & Jouault, S. C. (2014). Exopolysaccharides produced by marine bacteria and their applications as glycosaminoglycan-like molecules. *Frontiers in Chemistry*, 2, 85.
- Lynch, K. M., Zannini, E., Coffey, A., & Arendt, E. K. (2018). Lactic acid bacteria exopolysaccharides in foods and beverages: Isolation, properties, characterization, and health benefits. *Annual Review of Food Science and Technology*, 9(1), 155–176.
- Lynch, K. M., Zannini, E., Wilkinson, S., Daenen, L., & Arendt, E. K. (2019). [Title of the work needed].
- Mansfield, J., Genin, S., Magori, S., Citovsky, V., Sriariyanum, M., Ronald, P., ... & Foster, G. D. (2012). Top 10 plant pathogenic bacteria in molecular plant pathology. *Molecular Plant Pathology*, 13(6), 614–629.
- Meyer, D., & Henry, J. (Eds.). (2015). Chapter Two - Health benefits of prebiotic fibers. In *Advances in food and nutrition research* (pp. 47–91). Academic Press.
- Milani, J., & Maleki, G. (2012). Hydrocolloids in food industry. In B. Valdez (Ed.), *Food Industrial Processes—Methods and Equipment* (pp. 17–38). Intech.
- Mišurcová, L. (2011). Chemical composition of seaweeds. In *Handbook of marine macroalgae: Biotechnology and applied phycology* (pp. 171–192).
- Nishinari, K., Zhang, H., & Funami, T. (2009). Curdlan. In G. O. Phillips & P. A. Williams (Eds.), *Handbook of hydrocolloids* (pp. 567–591). CRC Press.
- Nwokocha, L. M., & Williams, P. A. (2020). Characterization of the polysaccharide from *Cola millenii* seeds. *International Journal of Biological Macromolecules*, 161, 643-647.
- Öner, E. T., Hernández, L., & Combie, J. (2016). Review of levan polysaccharide: From a century of past experiences to future prospects. *Biotechnology Advances*, 827–844.
- Ouwehand, A. (2012). Prebiotic developments. *Microbial Ecology in Health & Disease*, 2.
- Pateiro, M., Gómez, B., Munekeata, P. E. S., Barba, F. J., Putnik, P., Kovačević, D. B., & Lorenzo, J. M. (2021). Nanoencapsulation of promising bioactive compounds to improve their absorption, stability, functionality, and the appearance of the final food products. *Molecules*, 26, 1547.
- Ryan, P. M., Ross, R. P., Fitzgerald, G. F., Caplice, N. M., & Stanton, C. (2015). Sugar-coated: Exopolysaccharide producing lactic acid bacteria for food and human health applications. *Food & Function*, 6(3), 679–693.
- Saha, D., & Bhattacharya, S. (2010). Hydrocolloids as thickening and gelling agents in food: A critical review. *Journal of Food Science and Technology*, 47, 587–597.
- Salimi, F., & Farrokh, P. (2023). Recent advances in the biological activities of microbial exopolysaccharides. *World Journal of Microbiology and Biotechnology*, 39(8), 213.
- Sanchez, J. I., Martinez, B., Guillen, R., Diaz, R. J., & Rodriguez, A. (2006). Culture conditions determine the balance between two different exopolysaccharides produced by *Lactobacillus pentosus* LPS26. *Applied and Environmental Microbiology*, 72, 7495–7502.
- Ścieszka, S., & Klewicka, E. (2019). Algae in food: A general review. *Critical Reviews in Food Science and Nutrition*, 59(21), 3538–3547.
- Shetty, K., Paliyath, G., Pometto, A., & Levin, R. E. (2006). Biotechnology of microbial polysaccharides in food. In *Functional foods and biotechnology* (pp. 583–610). CRC Press.
- Singha, T. K. (2012). Microbial extracellular polymeric substances: Production, isolation and applications. *IOSR Journal of Pharmacy and Biological Sciences*, 2, 276–281.
- Sreekanth, M. S., Vijayendra, S. V. N., Joshi, G. L., & Shamala, T. R. (2013). Effect of carbon and nitrogen sources on simultaneous production of α -amylase and green food packaging polymer by *Bacillus* sp. CFR 67. *Journal of Food Science and Technology*, 50, 404–408.
- Srikanth, R., Reddy, C. H. S. S., Siddartha, G., Ramaiah, M. J., & Uppuluri, K. B. (2015). Review on production, characterization and applications of microbial levan. *Carbohydrate Polymers*, 102–114.
- Sutherland, I. W. (1990). Food usage of exopolysaccharides. In I. W. Sutherland

- (Ed.), *Biotechnology of microbial exopolysaccharides* (pp. 117-125). Cambridge University Press.
- Sutherland, I. W. (1995). Polysaccharide lyases. Sutherland Iw (1997), 'Bacterial exopolysaccharides-their nature and production, in *Surface Carbohydrates of the Prokaryotic Cell*, Sutherland IW (ed), Academic Press, London *FEMS Microbiology Reviews*, 16, 323–347.
- Sutherland, I. W. (1998). Novel and established applications of microbial polysaccharides. *Trends in Biotechnology*, 16, 41–46.
- Sutherland, I. W. (2001). Microbial polysaccharides from gram-negative bacteria. *International Dairy Journal*, 11, 663–674.
- Sutherland, I. W. (Ed.). (1990). *Biotechnology of microbial exopolysaccharides*. Cambridge University Press.
- Tomasik, P. (2004). *Chemical and functional properties of food saccharides*. CRC Press.
- Ul-Islam, M., Khan, S., Ullah, M. W., & Park, J. K. (2019). Comparative study of plant and bacterial cellulose pellicles regenerated from dissolved states. *International Journal of Biological Macromolecules*, 137, 247–252.
- Ullah, M. W., Ul-Islam, M., Khan, S., Shah, N., & Park, J. K. (2017). Recent advancements in bioreactions of cellular and cell-free systems: A study of bacterial cellulose as a model. *Korean Journal of Chemical Engineering*.
- Venugopal, V. (2011). Polysaccharides: Their characteristics and marine sources. In *Marine polysaccharides: Food applications* (pp. 3–27). CRC Press.
- Vijayendra, S. V. N., & Shamala, T. R. (2014). Film forming microbial biopolymers for commercial applications—a review. *Critical Reviews in Biotechnology*, 34, 338–357.
- Wüstenberg, T. (2015). General overview of food hydrocolloids. In T. Wüstenberg (Ed.), *Cellulose and cellulose derivatives in the food industry: Fundamentals and applications* (pp. 1–68).
- Yu, I., Kaonis, S., & Chen, R. (2017). A study on degradation behavior of 3D printed gellan gum scaffolds. *Procedia CIRP*, 65, 78–83.
- Zavareze, E. R., Kringel, D. H., & Dias, A. R. G. (2019). Nano-scale polysaccharide materials in food and agricultural applications. In L. T. Lim & M. Rogers (Eds.), *Advances in Food and Nutrition Research* (Vol. 88, pp. 85–128). Academic Press.
- Zhang, R., & Edgar, K. J. (2014). Properties, chemistry and applications of the bioactive polysaccharide curdlan. *Biomacromolecules*, 15, 1079–1096.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of the publisher and/or the editor(s). This publisher and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

© Copyright (2024): Author(s). The licensee is the journal publisher. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:

The peer review history for this paper can be accessed here:

<https://www.sdiarticle5.com/review-history/125905>