Annals of Phytomedicine 12(2): 200-207, 2023

DOI: http://dx.doi.org/10.54085/ap.2023.12.2.22

Annals of Phytomedicine: An International Journal
http://www.ukaazpublications.com/publications/index.php

Print ISSN : 2278-9839 Online ISSN : 2393-9885

Review Article : Open Access

Exopolysaccharides producing lactic acid bacteria from goat milk: Probiotic potential, challenges, and opportunities for the food industry

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Article Info

Article history
Received 20 June 2023
Revised 9 August 2023
Accepted 10 August 2023
Published Online 30 December 2023

Keywords
Exopolysaccharide
Functional foods
Goat milk
Health benefits
Lactic acid bacteria

Abstract

Exopolysaccharides (EPS) producing lactic acid bacteria (LAB) derived from goat milk have garnered significant attention in recent years due to their potential as probiotics. These beneficial microorganisms offer promising health benefits and play a crucial role in the food industry. The potential health benefits associated with probiotic LAB and their EPS, such as immunomodulation and gut health improvement, highlight their value for functional foods and nutraceuticals. The rheological and textural properties of EPS further contribute to their potential applications as stabilizers and thickeners in food formulations. This review article aims to explore the probiotic potential of EPS-producing LAB from goat milk, highlighting the challenges and opportunities it presents for the food industry.

1. Introduction

Lactic acid bacteria are gram-positive rods or coccus-shaped bacteria that use heterofermentative or homo-fermentative metabolism to produce lactic acid as the main end product. They are mostly present in traditional fermented foods like yogurt, sourdough, cheese, wine, sauerkraut, sausage, natto, olives, tempeh, *etc*., LAB are generally accepted as safe and have significant effects on human health (Meena *et al*., 2022). They produce various metabolites, such as 1,3-propanediol, fatty acids, organic acids, mannitol, and EPS, which are crucial to both the food and pharmaceutical industries. Milk and fermented milk products are the best sources of probiotics (Xu *et al*., 2019), especially goat milk, which offers numerous nutritional and functional benefits over cow milk. The EPS produced by lactic acid bacteria are potential bioactive compounds with health implications. These probiotics are gaining momentum in the food industry due to their immunomodulatory, antimicrobial, and cholesterol-lowering properties. Goat milk is a comparable alternative to cow's milk for human consumption, offering easy digestibility and a rich nutritional profile (Azhar *et al*., 2022). The EPS regulate intestinal microbial homeostasis and suppress pathogens and harmful bacteria in the gut mucosa, besides other crucial roles in the health and sickness of the host. They can be used as prebiotics in the food sector for positive benefits. Exopolysaccharides (EPSs) are important metabolites of LAB that can adhere to the surface of the bacterial cell to create capsular EPSs that are discharged into the surrounding environment as slime EPSs. The EPSs have various useful properties, including the ability to promote probiotic colonization in the host's gut and antioxidant, anticancer, antibacterial, hypoglycemic, and antihypertensive. EPS-producing LAB strains have received significant attention in recent studies, with a focus on immunological regulation and their potential applications in the food and pharmaceutical sectors. The EPS have unique physicochemical features that offer promise for the food and pharmaceutical sectors that can be used for protection against abiotic or biotic stress, pH, competition, and temperature (Jurášková *et al*., 2022). However, most studies focus on EPS in the food sector due to their structural qualities such as gelling, water retention, emulsification, sweetening, water-binding capacity, texturization, and bioactive properties. Recent research has shown that EPS-producing LAB isolates from goat milk have the potential to improve health through immunomodulatory, prebiotic, anti-inflammatory, antibiofilm, and antioxidant effects. Therefore, this review focused on the beneficial effect of isolating lactic acid bacteria strains capable of producing exopolysaccharides from goat milk, its application, challenge, and opportunities in the dairy and food industry.

2. Goat milk

India is the second largest country in goat milk production after China, and Rajasthan is the leading goat milk-producing state. Goat milk is a nutritious alternative to cow's milk, boasting various health benefits, easy digestibility, and a rich profile of essential nutrients (Premasiri *et al*., 2021). Goat milk contains a complex autochthonous microbiota responsible for spontaneous fermentation in food

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processing. This microbiota has a unique capacity to prevent colorectal and colon cancer (Mittu and Girdhar, 2016). Goat milk typically contains strains of the *Lactobacilli* species *L. plantarum, L. rhamnosus, L. casei, L. pentosus,* and *L. fermentum* (Bousmaha-Marroki and Marroki, 2015). Goat milk has garnered considerable attention within the scientific community as an attractive source for isolating probiotic or lactic acid bacteria. This interest arises from several advantageous qualities, such as enhanced digestibility, alkalinity, and superior buffering capacity when compared to cow and human milk. Furthermore, its distinctive composition and diverse nutritional value contribute to its appeal as a potential resource for such bacteria. According to Da Costa *et al.* (2014), goat milk has significant biological properties, including antibacterial, immune-modulatory, antioxidant, antithrombotic, hypocholesterolemic, and antihypertensive action. Goat milk's chemical composition is similar to that of human milk. According to Rai *et al.* (2022), goat milk's protein is digested more quickly, and its amino acids are absorbed more effectively than those found in other milk. In addition, their lack of mucus-producing substances and low-fat content make them the healthiest foods found in nature (Atanasova and Ivanova, 2010).

3. Probiotics

Lactic acid bacteria, one of the most prevalent bacterial genera, is used to enhance the sensory, flavor, texture, nutritional, and functional characteristics of fermented foods. *Lactobacilli* are gram-positive, non-spore-forming, either cocci or rod-shaped bacteria that do not produce endospores and are considered non-harmful. They are used in conventional fermentation to produce lactic acid but can also produce acetic acid, ethanol, carbon dioxide, or acetate. Lactic acid bacteria (LAB) dominate the probiotics used in the dairy and food industry for their essential contributions to food processing and nutrition. LAB are commonly employed as starter cultures in fermented food products. The primary and most prevalent lactic acid bacterial genus includes "*Enterococcus, Lactococcus, Lactobacillus, Leuconostoc, Vagococcus, Pediococcus, Streptococcus, Tetragenococcus, Vagococcus,* and *Weissella*" (Ayyash *et al.*, 2021; Meena *et al.*, 2023a).

Elie Metchnikoff theorized that altering the gut microbiome with host-friendly bacteria present in fermented dairy products may improve health and prevent the onset of senility more than a century ago. Probiotics are beneficial microorganisms that offer a host of advantages. They are added to food, dietary supplements, and pharmaceuticals in the hope that they will have positive health effects. The term "probiotic" was coined by Lilly and Stillwell (1965) to refer to "factors which promote the growth produced by microorganisms" and was later defined by the FAO/WHO Expert Panel in 2001 as "Live microorganisms that, when administered in adequate amounts, confer a health benefit on the host" LAB genera are classified into two categories: homo-fermentative and hetero-fermentative. Homo-fermentative LAB utilizes the Embden-Meyerhof-Parnas (EMP) pathway to catabolize one mole of glucose under limited oxygen, yielding lactic acid only, while hetero-fermentative LAB utilizes the pentose phosphate pathway. Probiotic bacteria are obtained from food items and impact the genetic makeup of the intestinal microbiota. These bacteria are responsible for digestive, gastrointestinal, and general well-being and are used in fermented foods that are good for human and animal health (Macelak *et al.*, 2022).

4. Exopolysaccharides

Bacteria have the capability to synthesize numerous distinct polysaccharides, which can be either tightly bound to the cell surface or secreted as exopolysaccharides. LAB can produce diverse EPSs, exhibiting vast structural variations, including differences in side chains, repeating unit linkages, substitutions, and charges. These EPSs consist of sugars such as arabinose, galactose, mannose, glucose, and derivatives like acetyl galactosamine and acetyl glucosamine. Their composition relies on factors like growth medium, cultural and bacterial strains, and EPS production involves proteins and enzymes subject to gene expression regulation (Prasad and Purohit, 2023).

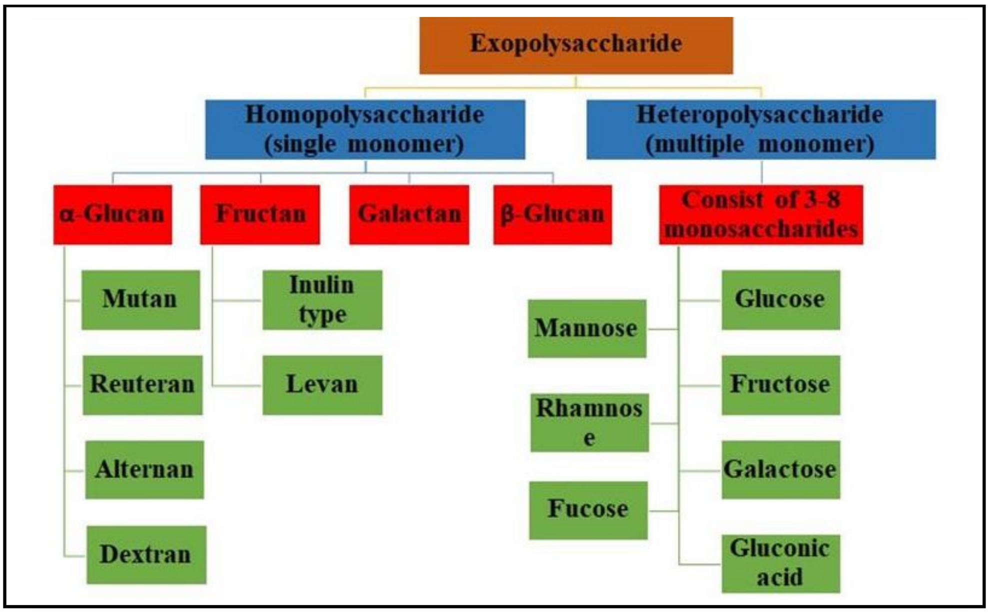

Figure 1: Type and composition of EPS.

Hetero-polysaccharides (Het-EPS) and homo-polysaccharides (Hom-EPS) are the two types of EPSs. Lactobacilli create homo-polysaccharides (Hom-EPSs), which are repeating units with a molecular weight of 10^5-10^6 Da (Prete *et al.*, 2021). Utilizing the energy from the glycosidic bonds between glucose and fructose, enzymes known as glycosyl hydrolases assist in the synthesis of α-glucans and α-fructans from these sugars. Based on the locations of the carbon bonds and the sorts of glycosyl groups, homo-EPSs may be divided into three different categories: polyglucans, D- α-glucans, and D-α-glucans. Different strains of Lactobacilli generate Hom-EPSs of various sorts, including mutan, dextran, reuteran, alternan, levan, lucans and insulin-type glucan (Bibi *et al.*, 2021). Het-EPS consist of different monosaccharides and encompass 3 to 8 repeating units of galactose, glucose, and rhamnose in varying quantities. These types of EPSs also contain uronic acid, acetyl-D-glucosamine, and acetyl-Dgalactosamine, which plays an important function in the techno-functional attributes (Sørensen *et al.*, 2022). The secretion of HePSs is influenced by various growth parameters, including pH, O_2 concentration, media composition, turbidity, temperature, growth phase, and the quantity and type of glycosidic linkages (Bibi *et al.*, 2021). The type and composition of EPS are represented in Figure 1.

These polysaccharides play a role as water-binding agents, enhancing moisture retention and reducing whey separation in dairy products (Prete *et al.*, 2021). Lactic acid bacteria can biosynthesize beneficial compounds like exopolysaccharides, including dextran, which show promise as immunomodulators or antiviral agents. LAB and other bacterial species produce exopolysaccharides (EPS) that are used as viscosifiers, emulsifiers, or gelling agents in the production of fermented dairy products. EPS also exhibits beneficial effects on human health. These strains can be used in the dairy industry and pharmaceutical industries as food additives (Sørensen *et al.*, 2022).

5. Probiotic potential of EPS producing LAB

LAB have demonstrated their potential as probiotics and are used in various applications, including as starter cultures in yogurt, cheese, buttermilk, fermented meat, and fermented vegetables. *Lactobacillus* genus includes species like *L. acidophilus, L. delbrueckii, L. helveticus, L. salivariu*s, *etc*., that ferment sugar to lactic acid. The origin of these isolates varies across research studies and geographical regions, which can impact their effectiveness (Yang *et al.*, 2023). Goat milk has several advantageous qualities, including enhanced digestibility, alkalinity, and superior buffering capacity when compared to cow and human milk. It is distinctive composition and diverse nutritional value contribute to its appeal as a potential resource for isolating probiotic or lactic acid bacteria (Premasiri *et al.*, 2021). Researchers have focused on isolating, evaluating, and characterization of *in vivo* and *in vitro* identification of industrially beneficial EPS-producing probiotic lactic acid bacteria from milk. Various findings demonstrate that EPS has strong antioxidant activity (Kanmani *et al.*, 2018). The LAB have shown promising potential in reducing harmful free radicals responsible for initiating and advancing various disease conditions. The EPS derived from *Lactobacillus plantarum* C88 can help counteract oxidative stress and its detrimental effects, providing potential health benefits (Zhang *et al.*, 2013). LAB isolates that produce EPS are well-tolerant to gastrointestinal issues and have good antimicrobial activity. Xu *et al.* (2023) isolated ten distinct *Lactobacillus* strains from broiler chickens and found that the LR 21 strain, in particular, performed exceptionally well in terms of auto-aggregation, hydrophobicity, and adhesion to $CaCO_2$ intestinal cells. The researchers used TOPSIS ("Technique for Order Preference by Similarity to Ideal Solution") to select the most promising probiotic candidate. They found that EPS-producing LAB strains demonstrated good adhesion to the gastrointestinal mucosa. The researchers also assessed the potential of these strains as probiotics and antagonists against food-associated microbes. Newly obtained LAB strains exhibited antagonistic effects against *Pseudomonas aeruginosa, Escherichia coli, Bacillus subtilis,* and *Bacillus cereus*, as well as promising antifungal potential. Additionally, the strains showed strain-specific aggregation, hydrophobicity of the cell surface, and mucin adhesive properties. Gizachew *et al.* (2023) have isolated LAB strains that produce EPS have strong antagonistic potentials. Five strains derived from cottage cheese demonstrated inhibitory activity against indicator pathogens responsible for gastrointestinal infections in Ethiopia. Researchers tested LAB isolates for immunomodulatory activity, and results show that five strains show promising results based on antibiotic resistance profiles. These isolates are considered novel probiotic candidates of interest for further clinical investigation.

Ansari *et al.* (2023) isolated *Saccharomyces boulardii*, a strain of *Saccharomyces cerevisiae*, from various sources and demonstrated that it has potential probiotic properties, including lowering blood cholesterol levels and demonstrating anticarcinogenic, antibacterial, antiviral, and antioxidant actions. Maciel *et al.* (2016) isolated three *Lactobacillus mucosae* strains from goat milk, and Cho *et al.* (2018) evaluated the LAB stain *Lactobacilli* to develop starter cultures from fermented goat milk products of Tajikistan for their technical characteristics and antibiotic resistances. Twenty-three strains of lactic acid bacteria were recognized by 16S rDNA sequencing as classic dairy-associated LAB bacterial strains. The delineation genomes of 4 representative strains were screened and sequenced, and the pH of fermented milk products from Tajikistan dropped to 3.4 when the strains were co-injected with yeast. The study done by Delgado *et al.* (2015) identified ten distinct *Lactobacilli* strains from healthy individuals' stomachs through PFGE fingerprinting and rep-PCR. These strains belonged to five different species. All ten strains of *L. reuteri* demonstrated strong resilience to low pH, and none exhibited unusual resistance to a group of 16 important clinical and veterinary medications.

In another study, five probiotic strains were selected from fermented goat milk samples, and they showed excellent anti-Helicobacter and antioxidative activity, as well as good survival under gastrointestinal conditions recreated *in vitro* (Liu *et al.*, 2023). The study reported purification and identification of EPS produced by five lactic acid bacterial strains, *viz*., "*Lactiplantibacillus plantarum* 7830, *Limosilactobacillus fermentum* B55, *Limosilactobacillus fermentum* B62 *Pediococcus acidilactici* B30, and *Lactobacillus helveticus* K2." Moreover, the two *L. reuteri* strains showed favourable technical characteristics for their potential use as auxiliary functional cultures in fermented dairy products. The selected LAB strains demonstrated resilience to both high and low temperatures and coagulation ability in skimmed milk. They also had the highest lactic acid production capacities (Picon *et al.*, 2016). da Silva *et al.* (2019) investigated several factors in selected LAB strains and found that *Lactococcus lactis* (DF04Mi) and *L. plantarum* (DF60) were more resistant to simulated digestive conditions, indicating their potential suitability for incorporation into meals. *Lactococcus lactis* (DF04Mi) and *L. plantarum* (DF60Mi) produce EPS and exhibit antibacterial effects against *Streptococcus mutans*, making them potentially beneficial for oral health applications. Srinivash *et al.* (2023) isolated four LAB strains from handmade fermented food items and found that they had broad inhibitory ability against test indicators, high acid resistance, and good auto-aggregation capability. They also showed good cholesterol absorption capacity. Based on their overall score of 95.83%, these four *Lactobacillus bulgaricus* strains were considered to have significant potential for producing probiotic food items. Azhar *et al.* (2022) conducted a study to evaluate the potential of probiotic strains and the safety of lactic acid bacteria isolated from raw goat milk. They found that three LAB isolates had excellent antibacterial activity against all foodborne pathogens and demonstrated probiotic and technical features, making them suitable as starting cultures. Perin and Nero (2014) conducted a study on the microbiota of raw goat milk and discovered a novel bacteriocin-producing LAB strain with a broad inhibitory range. This LAB strain may be used as a bio-preservative in food products due to its broad spectrum of action against various pathogens. Patil *et al.* (2015) and colleagues discuss the different methods used to isolate EPS-producing LAB from dairy products, and Prasad and Purohit (2023) describe the various techniques used to characterize EPS-producing LAB. These LAB strains have been used to develop functional dairy products with enhanced health benefits.

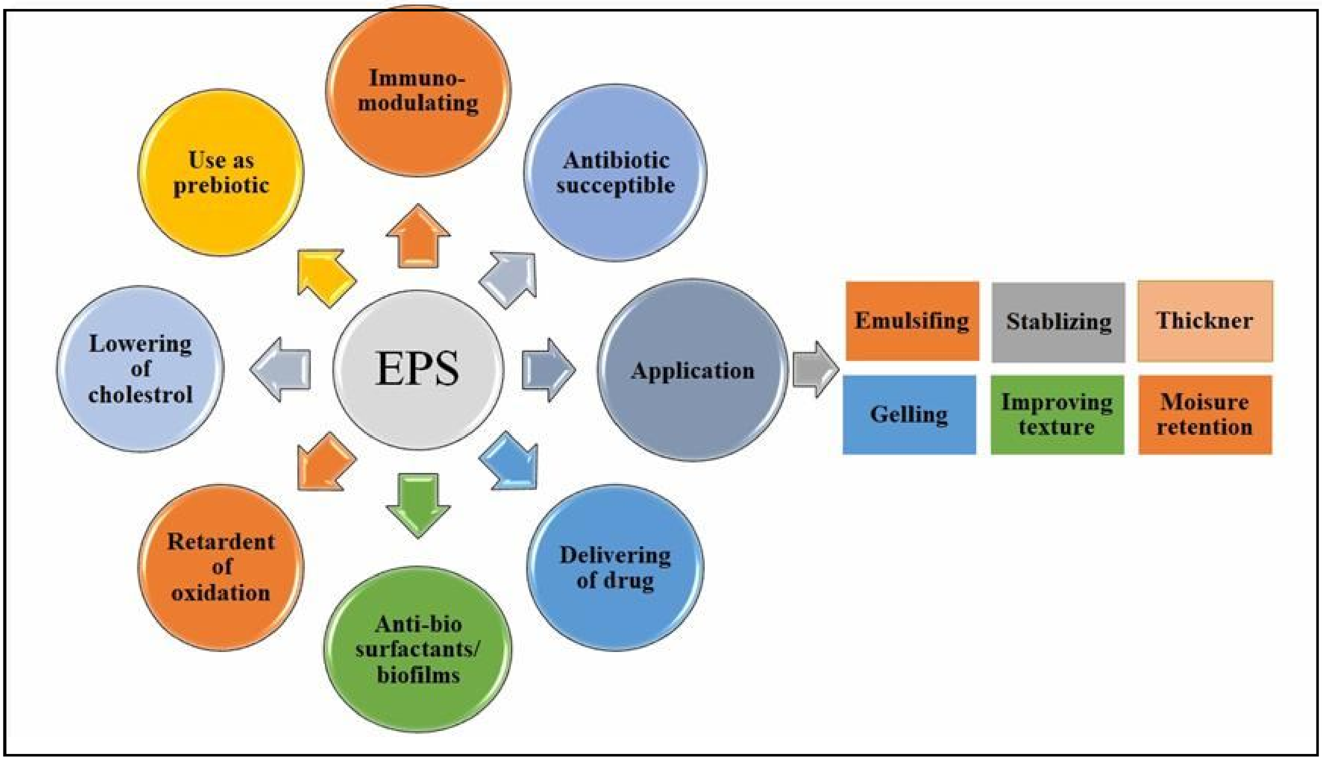

Figure 2: Biological application of EPS-producing LAB.

6. Application of EPS-producing LAB

Several researchers have done experiments to isolate and identify EPS-producing LAB from goat milk. These EPS-producing LAB strains have potential applications in the dairy and food industry as a thickening and meta-stabilizing agent and have prebiotic activity and immunomodulatory effects. In a study conducted by Zhao and Liang (2022) had shown the footprints of probiotic *L. plantarum* MC-5 on yogurt quality attributes, antioxidant activity, and storage steadiness. Four groups were created using various ratios of commercial starters and the probiotic *L. plantarum* MC-5. The highest EPS content was achieved in 2:1 and 1:1 yogurt samples. The study found favorable rheological properties, texture, and health effects, suggesting potential for industrial application in milk fermentation. The study suggests that LAB-derived EPS has significant potential as a sustainable and cost-effective tool for producing functional foods with health benefits. Jurášková *et al.*, (2022) explored the biosynthesis of LAB that produces EPS, which involves the expression of particular genes and the activity of various enzymes. The EPS has been shown to have a variety of health-promoting properties, including the ability to reduce inflammation and promote wound healing (Korcz and Varga, 2021). Wang *et al.* (2022) isolated *Lacticaseibacillus paracasei* GL1 and obtained two exopolysaccharide fractions, GL1-E1 and GL1-E2, which were found to have excellent thermal stability and enhance phagocytosis, increase nitric oxide release, and stimulate cytokine production in RAW 264.7 cells. The isolated *Lacticaseibacillus paracasei* GL1 strain characterized two exopolysaccharide fractions, GL1-E1 and GL1-E2, from Taiwanese ropy fermented milk, with the goal of creating a low-fat fermented milk product with a clean label. The authors used EPS producing lactic acid bacteria to create a low-fat fermented milk product with promising physical and sensory characteristics. The product displayed good physical characteristics and a stable pH value, acidity, syneresis, and sufficient viable cells over a 21-day storage test. Majee *et al.* (2017) have created nanoparticles from EPS that self-assembled and were loaded with anticancer medications like epirubicin. These nanoparticles increased the drug's absorption in animals with tumors. The food industry has shown significant interest in the synthesis of EPS by LAB, as these compounds enhance the rheological characteristics of fermented foods, make them natural thickeners, and have been shown to have positive effects on gut flora regulation and overall health. A thorough investigation was conducted to pinpoint the variables that affect EPS production as well as strategies for its extraction, characterization, and measurement. EPS is a metabolite that LAB can produce during fermentation that can be advantageous to human health. The other significant studies are summarized in Table 1.

Table 1: Functional attributes of EPSs producing LAB strains

Species	Strain	Functional attributes	References
Streptococcus thermophilus	S-3	Yogurt with increased viscosity and a thicker mouthfeel	Xu *et al.*, 2018
Lactobacillus delbrueckii ssp. *bulgaricus*	LBB.B26	Boost the viscosity of the yogurt	Sánchez-Medina *et al.*, 200
L. plantarum	JLK0142	immune modulating, antioxidant, anticancer	Wang *et al.*, 2018
L. acidophilus	E25	Anticancer dertli	El-Deeb *et al.*, 2018
L. paracasei	DG	Immune modulating	Balzaretti *et al.*, 2017
L. casei	LC2W	Antihypertensive	Al-Daheri *et al.*, 2017
L. johnsonii	FI9785	Promote colonization of strains	Dertli *et al.*, 2018
Weissella hellenica	SKkimchi3	Texturing, thickening, gelling, stabilizing, emulsifying agents, and antibacterial	Kavitake *et al.*, 2016
Pediococcus acidilactici	M76	Antioxidant Antidiabetic	Song *et al.*, 2013
Leuconostoc kimchii	GJ2	Antimicrobial	Ju and Jung , 2013
Enterococcus faecium	ISO13	Milk coagulation potential, amylolytic activity, susceptibility to antibiotics	Azhar *et al.*, 2022

7. Safety

The EPS produced by LAB may be subject to regulatory scrutiny, particularly if intended for human consumption. Ensuring safety, compliance with standards, and proper labeling are important aspects of bringing LAB-produced EPS to market (Jurášková *et al.*, 2022). FAO/WHO (2002) guidelines recommend identifying probiotics at the strain level, testing them *in vivo* and *in vitro* for functionality and safety, and conducting clinical trials on humans. "The Department of Biotechnology (DBT)" and the "Indian Council of Medical Research (ICMR)" developed a guideline for the characterization of probiotics for the Indian market in 2011, which includes recommendations on product safety, health claims, and labelling problems.

8. Challenges in production of exopolysaccharides using LAB

While EPS-producing LAB from goat milk offers numerous advantages, however, their production and application present several intricate challenges that must be navigated for successful and efficient manufacturing. The production and extraction of exopolysaccharides can be complex and costly. Additionally, strain-specific considerations, stability during food processing, and regulatory approval are some of the hurdles that need to be addressed. The selection of a LAB strain with high EPS-producing potential is a critical initial step. The different EPS-producing LAB strains exhibit varying abilities for EPS production, which depends on genetics, growth conditions, and substrate availability (Mýdýk *et al.*, 2020). The maximum EPS yield and characteristics can be achieved by optimizing strain for specific applications (Meena *et al.*, 2023b). The optimization of fermentation conditions is also an essential step to maximize EPS production. The EPS biosynthesis during fermentation depends on parameters such as pH, temperature, carbon source, and nitrogen availability. Maintaining consistent and optimal conditions throughout the fermentation process is challenging, as changes can affect EPS yield, molecular weight, and structural properties (Jurášková *et al.*, 2022). The growth media (carbon source) significantly affects EPS biosynthesis during fermentation. The fermenting LAB requires specific carbon sources, often in the form of sugars, to produce EPS. Identifying cost-effective and sustainable carbon sources that promote high EPS yields while minimizing by-product formation is complex (Srinivash *et al.*, 2023). Maintaining aseptic conditions during LAB fermentation is crucial to prevent contamination by unwanted microorganisms. Even minor contamination can alter the composition and properties of EPS, impacting product consistency and quality. Recovering EPS from fermentation broth presents significant challenges. EPS extraction, purification, and concentration methods must be developed to yield high-purity EPS with minimal degradation. These processes are often complex, involving techniques such as precipitation, ultrafiltration, and chromatography (Rana and Upadhyay, 2020).

EPSs produced by LAB are structurally diverse, comprising various sugar units and glycosidic linkages. This heterogeneity poses challenges in terms of analyzing, characterizing, and modifying EPS for specific applications. Determining the optimal structural features to achieve desired functionalities is a complex undertaking. Maintaining consistent EPS quality and properties across batches is essential for commercial applications. Variability in fermentation conditions, strain behaviour, and downstream processing can lead to variations in EPS characteristics, necessitating robust quality control measures (Meena *et al.*, 2023b). Scaling up EPS production from laboratory to industrial scales introduces engineering and economic challenges. Ensuring efficient heat and mass transfer, maintaining optimal fermentation conditions, and managing resource consumption requires careful consideration (Bunkar *et al.*, 2020). Products derived from LAB-produced EPS may be subject to regulatory scrutiny, particularly if intended for human consumption. Ensuring safety, compliance with standards, and proper labeling are important aspects of bringing LAB-produced EPS to market (Jurášková *et al.*, 2022).

9. Opportunities for the food industry

The food industry has a unique opportunity to harness the potential of EPS-producing LAB from goat milk in developing functional foods and beverages. The production of exopolysaccharides (EPS) by certain strains of LAB introduces an additional dimension to their potential applications, offering various opportunities for enhancing food quality, shelf-life, and nutritional value. Incorporating these bacteria into dairy-based products, such as yogurt and cheese, can enhance their nutritional value and improve their shelf life. Furthermore, developing novel probiotic supplements and formulations presents an avenue for the industry to explore.

EPS production by LAB can enhance the viscosity, mouthfeel, and overall texture of food products. This is particularly relevant for dairy products like yogurts, where EPS can improve creaminess and stability or in spreads and sauces to achieve desired consistency. The use of EPS producing LAB can aid in stabilizing emulsions, which is crucial for products like salad dressings, sauces, and mayonnaise. The emulsifying properties of EPS can lead to improved product stability and reduced separation over time. The EPS act as natural preservatives, helping to extend the shelf life of various food products. Their ability to retain moisture and inhibit the growth of spoilage microorganisms can be advantageous for perishable items such as bakery goods, fermented beverages, and ready-to-eat meals. Some EPS produced by LAB possesses prebiotic properties, promoting the growth of beneficial gut bacteria and contributing to improved digestive health. Incorporating EPS-producing LAB into functional foods like probiotic yogurt or fermented beverages can offer consumers an added health dimension. Using EPS-producing LAB aligns with the growing consumer demand for clean labels and natural ingredients. EPS can replace or reduce the need for artificial thickeners, stabilizers, and preservatives in food formulations. EPS production by LAB can utilize agricultural by-products or food industry waste streams as substrates. This approach contributes to waste reduction, sustainability, and efficient resource utilization.

10. Conclusion

In conclusion, the investigation of EPS generated by LAB is a dynamic field of study with important ramifications for both industry and public health. Probiotics made from goat milk that produce exopolysaccharides have a lot of potential for use in the food sector and offer considerable health advantages. In conclusion, the probiotic potential of EPS-producing LAB from goat milk opens up promising opportunities for the food sector to develop healthier and more useful goods that can improve human well-being. The full potential of these helpful microbes will surely be realized as a result of future studies and technological developments. However, the production of EPS by LAB is a complex endeavor that involves addressing numerous challenges across strain selection, fermentation, downstream processing, and product standardization. Overcoming these challenges requires a multidisciplinary approach involving expertise in microbiology, biotechnology, engineering, and regulatory affairs, to unlock the full potential of EPS for a wide range of applications.

Acknowledgements

The authors are thankful to the College of Dairy and Food Technology, Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan, India for providing necessary facilities.

Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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Citation	Deepak Meghwal, Kamalesh Kumar Meena, Rahul Singhal, Lokesh Gupta and Naryan Lal Panwar (2023). Exopolysaccharides producing lactic acid bacteria from goat milk: Probiotic potential, challenges, and opportunities for the food industry . Ann. Phytomed., 12(2):200-207. http://dx.doi.org/10.54085/ap.2023.12.2.22.