UDK: 579.67:637.146

Muattar Absalamovna Khudzhanova[1], *Rakhimova Diyora Davlarovna*[2]*
Alimova Ozoda Bekmurodovna[3], *Usmonkulova Gulsevar Jamshidovna*[4]*

[1] *Department of Physiology, Pathophysiology, and Hygiene, Zarmed University, Samarkand, Uzbekistan*
[2] *Master's Student, KIUT Samarkand Branch, Samarkand, Uzbekistan*
[3] *Department of Physiology, Samarkand State Medical University , Uzbekistan*
[4] *School of Life Sciences, University of Glasgow, Glasgow, United Kingdom*

METABOLIC ACTIVITY OF LACTIC ACID BACTERIA IN TRADITIONAL FERMENTED DAIRY PRODUCTS AND ITS ROLE IN PROBIOTIC FUNCTIONALITY

Abstract

Traditional fermented dairy products represent complex microbial ecosystems in which lactic acid bacteria (LAB) play a central role in determining product quality, safety, and potential health benefits. These products, including region-specific varieties such as qatiq, chakki, chalob, and qurtob, are produced through spontaneous or semi-controlled fermentation processes that promote diverse and metabolically active microbial communities. While previous studies have largely focused on the taxonomic composition of LAB in fermented dairy systems, increasing attention is being directed toward their metabolic activity and its functional implications.

This review examines the metabolic processes of LAB in traditional fermented dairy products, with emphasis on carbohydrate fermentation, organic acid production, exopolysaccharide synthesis, antimicrobial compound formation, and flavour-related metabolism. These biochemical activities contribute to key technological outcomes, including acidification, preservation, texture development, and sensory characteristics. At the same time, they are closely linked to probiotic-associated traits such as pathogen inhibition, gastrointestinal survival, and potential modulation of host microbiota.

Furthermore, traditional fermented dairy products serve as important reservoirs of diverse LAB strains with functional and technological potential. However, probiotic effects remain strain-specific and require careful evaluation through mechanistic and clinical studies. A deeper understanding of LAB metabolism within these traditional systems may support the development of improved functional foods and novel probiotic applications.

Keywords

Lactic acid bacteria, Fermented dairy products, Traditional fermentation, Probiotic functionality, Metabolic activity, Exopolysaccharides, Bacteriocins

Introduction

Fermented dairy products have been an integral component of human nutrition for centuries, serving both as a method of preservation and as a source of enhanced sensory and nutritional qualities. Across diverse geographical regions, traditional products such as yogurt, kefir, qatiq, chakki, chalob, and qurtob are produced through spontaneous or semi-controlled fermentation processes involving complex microbial communities [1,2]. These products are characterized by unique textures, flavours, and extended shelf life, which are largely determined by the metabolic activity of lactic acid bacteria (LAB) [3].

Lactic acid bacteria represent a diverse group of Gram-positive, acid-tolerant microorganisms that play a central role in milk fermentation. Their primary metabolic function involves the conversion of carbohydrates, particularly lactose, into lactic acid, resulting in rapid acidification of the dairy matrix [3,4]. This acidification inhibits spoilage organisms and pathogenic bacteria while promoting protein coagulation and contributing to desirable organoleptic properties [1,5]. In addition to organic acid production, LAB are capable of synthesizing a wide range of metabolites, including exopolysaccharides, bacteriocins, and flavour-active compounds, which collectively influence product quality and safety [4,5].

Traditional fermented dairy systems often rely on natural fermentation or back-slopping practices, leading to highly diverse and dynamic microbial populations shaped by environmental conditions, raw materials, and local production methods [2,6]. These artisanal systems are increasingly recognized as important reservoirs of functionally significant LAB strains with both technological and probiotic potential [7]. Such diversity is particularly evident in underexplored regional products, including those from Central Asia, where traditional fermentation practices remain largely unstandardized yet biologically rich.

Despite extensive research on fermented dairy microbiota, much of the existing literature has focused on identifying the microbial composition of these products rather than understanding the functional implications of microbial activity [2]. However, the technological and health-related properties of fermented dairy products are primarily determined by the metabolic processes carried out by LAB [8,4]. These processes generate compounds that influence preservation, texture, flavour development, and interactions with the host gastrointestinal environment [8,9]. This review examines how the metabolic activity of lactic acid bacteria in traditional fermented dairy products contributes to both fermentation processes and probiotic functionality.

2. Lactic Acid Bacteria in Traditional Fermented Dairy

Lactic acid bacteria (LAB) are the dominant microbial group involved in the fermentation of dairy products and play a central role in determining their quality, safety, and functional properties. Common genera associated with fermented dairy systems include Lactobacillus (recently reclassified into genera such as Lacticaseibacillus), Lactococcus, Streptococcus, and Leuconostoc, each contributing distinct metabolic capabilities that influence the fermentation process [3,6]. These microorganisms are widely distributed across a range of traditional and industrial dairy products, including yogurt, kefir, dahi, suzma, and various artisanal cheeses [1,3].

Traditional fermented dairy products are typically produced through spontaneous fermentation or back-slopping methods, in which a portion of a previously fermented product is used to inoculate fresh milk. Unlike controlled industrial fermentations that rely on defined starter cultures, these traditional processes allow for the development of complex and dynamic microbial communities [1,2]. As a result, the composition of LAB populations can vary significantly depending on environmental conditions such as temperature, milk source, hygiene practices, and fermentation duration [2,6]. This variability contributes to the rich microbial diversity observed in traditional dairy systems, particularly in region-specific products such as qatiq, chakki, chalob, and qurtob **(Figure 1).** These products, often produced under artisanal conditions, represent unique ecological niches in which diverse LAB strains coexist and interact. Such environments promote the selection of microorganisms that are well adapted to local conditions, including tolerance to acidity, osmotic stress, and nutrient limitations [6,7].

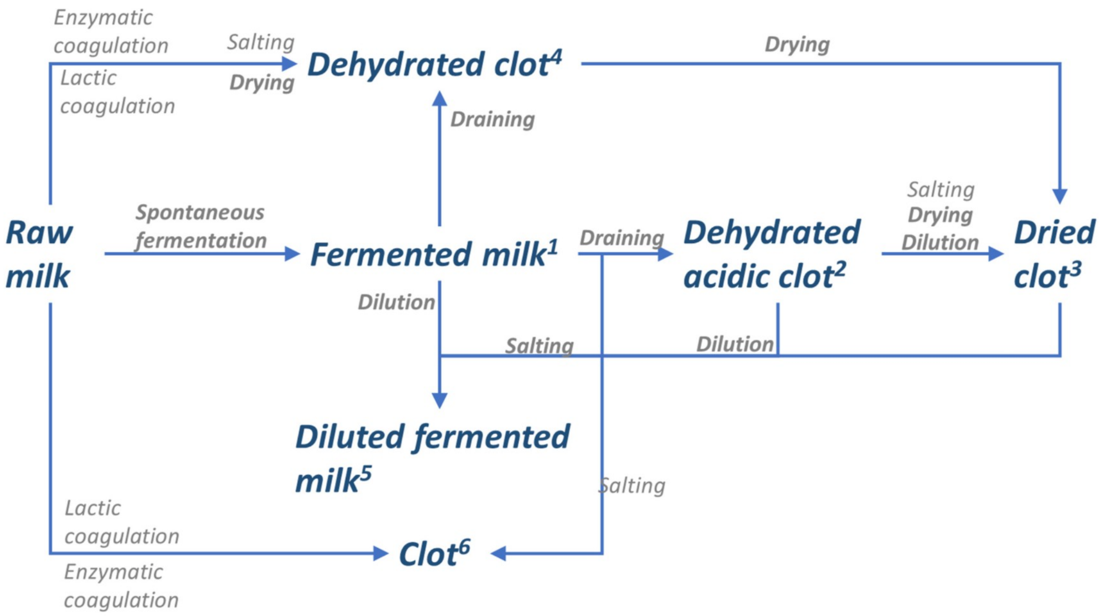

Figure 1. Processing relationships among traditional fermented dairy products in Central Asia. Listed products are: 1, ayran, tarag, shubat or qymyz; 2, qatyq; 3, qurt; 4, suzbe or syzma; 5, tan, chal or shalap; 6, irimshik. Adapted from [1].

The environment in which fermentation occurs plays a critical role in shaping microbial composition and activity. Factors such as raw milk microbiota, fermentation vessels, and repeated back-slopping cycles can influence both the diversity and stability of LAB populations over time [1,6]. This ecological complexity is particularly important in traditional systems, where microbial interactions contribute not only to product characteristics but also to the emergence of strains with desirable technological and functional traits [7]. Consequently, traditional fermented dairy products are increasingly recognized as valuable reservoirs of LAB with potential applications in food technology and probiotic development. However, the functional significance of these bacteria depends more on their metabolic activity than on their taxonomic identity alone. While the presence of specific genera provides useful information, it is ultimately the biochemical processes carried out by these microorganisms that determine their contribution to fermentation outcomes and probiotic-associated functionality [8,9]. The major LAB genera associated with traditional fermented dairy products and their general functional roles are summarized in **Table 1**.

Table 1. Major lactic acid bacteria genera associated with traditional fermented dairy products and their general functional roles.

Genus	Examples of associated products	General functional role
Lactobacillus / *Lacticaseibacillus*	Kefir, yogurt, qatiq, suzma	Acid production, stress tolerance, contribution to fermentation stability
Lactococcus	Cheese, cultured milk products	Rapid acidification, possible bacteriocin production
Streptococcus	Yogurt, fermented milk products	Fast fermentation and acid production
Leuconostoc	Traditional fermented dairy products, artisanal dairy systems	Flavour development, heterofermentation, exopolysaccharide production

3. Metabolic Activities of LAB in Dairy Fermentation

3.1 Carbohydrate metabolism and lactic acid production

The central metabolic role of lactic acid bacteria (LAB) in dairy fermentation is the conversion of lactose, the main sugar in milk, into organic acids, primarily lactic acid. Lactose is first hydrolysed into glucose and galactose, which then enter glycolytic pathways and are metabolised to pyruvate. Under fermentative conditions, pyruvate is mainly reduced to lactic acid, allowing LAB to generate energy while regenerating NAD+ required for continued glycolysis [10,11].

This process is the biochemical basis of dairy fermentation and is one of the defining functional traits of LAB.

LAB may be broadly classified as homofermentative or heterofermentative according to their carbohydrate metabolism. Homofermentative LAB convert most of the available sugar into lactic acid, leading to rapid acidification of the dairy matrix. In contrast, heterofermentative LAB produce lactic acid together with other metabolites such as acetic acid, ethanol, and carbon dioxide [10,12]. This distinction is important because it influences not only the rate of acid production but also the final sensory and structural properties of fermented dairy products. Homofermentative bacteria are particularly important in products where rapid pH reduction is needed, whereas heterofermentative organisms may contribute more strongly to flavour complexity and gas formation in certain traditional products [10,12].

The accumulation of lactic acid causes a decrease in pH, which is one of the most important technological consequences of LAB metabolism. Acidification inhibits the growth of many spoilage organisms and foodborne pathogens, thereby improving the microbiological safety and shelf life of fermented milk products [4,5]. At the same time, the drop in pH promotes destabilization and coagulation of milk proteins, especially caseins, which is essential for the formation of yogurt-like gels and other fermented dairy textures [13]. In practical terms, acid production transforms milk from a highly perishable raw material into a more stable and organoleptically distinctive food.

Acidification not only stabilizes the product but also creates selective pressure that shapes microbial succession. As pH falls during fermentation, acid-tolerant microorganisms become more competitive, whereas many non-adapted bacteria are progressively excluded [1,6]. This helps explain why traditional fermented dairy systems often become dominated by specific LAB populations over time, even when fermentation begins with a much more diverse microbial community. In this way, carbohydrate metabolism is not merely a source of energy for LAB but also a major ecological force structuring the fermentation environment [1,10].

3.2 Proteolysis and peptide formation

Although milk is rich in protein, many LAB cannot directly utilize intact casein molecules and therefore depend on proteolytic systems to access nitrogen sources required for growth. These systems typically involve extracellular or cell-envelope proteinases that hydrolyse caseins into oligopeptides, followed by peptide transport into the cell and further degradation by intracellular peptidases into smaller peptides and amino acids [11,14]. This proteolytic activity is essential in milk because the concentration of free amino acids is relatively low, making protein breakdown a necessary adaptation for bacterial growth in dairy environments. The products of proteolysis serve more than a nutritional role. Released peptides and amino acids support microbial growth and also act as precursors for additional metabolic pathways involved in flavour formation and functional activity [11,15]. Amino acids derived from casein degradation may be further converted into aldehydes, alcohols, acids, and sulfur-containing compounds that contribute to the sensory profile of fermented dairy products [15]. In this way, proteolysis links nutritional metabolism with technological quality.

Proteolysis has also attracted attention because some peptides released during milk fermentation may possess bioactive properties. Certain milk-derived peptides have been associated in the literature with antihypertensive, antimicrobial, antioxidant, or immunomodulatory effects, although these activities are often demonstrated under experimental conditions and should not automatically be interpreted as clinically proven benefits in humans [16]. For this reason, it is more accurate to state that LAB proteolysis may contribute to the release of potentially bioactive peptides rather than making broad health claims. Overall, proteolytic metabolism is fundamental to LAB survival in milk and significantly contributes to the nutritional and sensory complexity of fermented dairy products [11,16].

3.3 Exopolysaccharide (EPS) production

Some LAB synthesize exopolysaccharides (EPS), which are extracellular carbohydrate polymers released into the surrounding matrix during growth. In fermented dairy products, EPS production is particularly important because it directly affects rheological properties such as viscosity, texture, and mouthfeel [17,18]. When produced in situ during milk fermentation, EPS can act as natural biothickeners, improving product consistency and reducing syneresis, or whey separation, which is a common quality issue in fermented milk products [17].

From a technological perspective, EPS-producing LAB are valuable because they can improve texture without the need for added stabilizers. This is especially relevant in yogurt and other cultured dairy products, where consumer preference often depends on creaminess, smoothness, and water-holding capacity [17,18]. EPS can therefore enhance both product quality and consumer acceptance while supporting cleaner-label formulations. Their production is strain-dependent and influenced by fermentation conditions, substrate availability, and the composition of the dairy matrix [18].

Beyond texture, EPS may also have functional biological significance. Several studies suggest that EPS can contribute to bacterial stress tolerance by forming a protective layer around the cell, which may reduce the impact of acid, osmotic stress, or other environmental challenges [18,19]. EPS have also been discussed in relation to host interaction, including possible roles in adhesion, immune modulation, and prebiotic-like effects, although these properties vary considerably depending on the structure of the polymer and the producing strain [18,19]. Therefore, as with other probiotic-associated traits, the significance of EPS should be interpreted cautiously and at the strain level rather than generalized across all LAB. Even so, EPS production remains one of the most important examples of how microbial metabolism can simultaneously influence food technology and potential biological functionality [17,19].

3.4 Bacteriocins and antimicrobial metabolites

In addition to lactic acid, LAB produce a variety of antimicrobial compounds that help suppress competing microorganisms during fermentation. Among the most studied of these are bacteriocins, which are ribosomally synthesized antimicrobial peptides produced by certain bacterial strains [4,20]. Bacteriocins can inhibit closely related bacteria and, in some cases, important foodborne pathogens, making them highly relevant to food preservation and safety [20,21].

LAB-mediated antimicrobial activity is not limited to bacteriocins alone. Organic acids such as lactic acid lower environmental pH and disrupt microbial homeostasis, while other metabolites such as hydrogen peroxide may further inhibit sensitive microorganisms [4,5]. The combined action of low pH, reduced redox potential, and antimicrobial molecules can create a strong barrier against spoilage organisms and pathogens in fermented dairy products [5,21]. This is one of the reasons why fermented milk products often show improved microbiological stability compared with raw milk.

Bacteriocin-producing LAB have attracted particular attention as natural bioprotective cultures in dairy systems. Their use may reduce reliance on chemical preservatives while enhancing product safety in cheeses, cultured milks, and other fermented products [20,21]. However, the antimicrobial spectrum of bacteriocins is highly variable, and not all LAB strains produce them. Moreover, the effectiveness of a bacteriocin in a food matrix depends on environmental factors such as pH, salt concentration, temperature, and the composition of the product [20]. From a functional perspective, antimicrobial metabolite production is also relevant to probiotic-associated activity, since the ability to inhibit pathogens is often considered a desirable trait in candidate probiotic strains [8,9]. Still, it is important to distinguish between antimicrobial effects observed in vitro and confirmed health benefits in vivo. Within dairy fermentation, the most immediate importance of bacteriocins and related metabolites lies in their contribution to microbial competition, product safety, and preservation [4,20].

3.5 Flavor and aroma compound production

LAB also contribute significantly to the flavour and aroma of fermented dairy products through the production of volatile and non-volatile metabolites. Important compounds include diacetyl, acetaldehyde, acetoin, organic acids, and other aroma-active molecules derived from pyruvate, citrate, and amino acid metabolism [15]. These metabolites are essential for the characteristic sensory profiles of many fermented dairy foods. For example, acetaldehyde is a key aroma compound in yogurt, while diacetyl contributes buttery notes in cultured dairy products [13,15]. Citrate metabolism and amino acid catabolism are especially important in flavour development. Through these pathways, LAB generate compounds that contribute to freshness, creaminess, buttery aroma, and overall complexity [15]. In mixed-culture fermentations, interactions between strains can further influence flavour formation by altering precursor availability and metabolic balance [15]. This helps explain why traditional products produced under artisanal conditions often develop more complex flavour profiles than highly standardized industrial products. The sensory consequences of LAB metabolism are not trivial. Flavour and aroma strongly influence consumer acceptance, which in turn affects the practical success of fermented dairy as a functional food. Even the most nutritionally promising product is unlikely to be consumed regularly if its texture or flavour is poor. For that reason, flavour-related metabolism should be understood as a major component of LAB functionality in dairy fermentation rather than a secondary aesthetic feature [13,15]. The principal metabolic activities of LAB in dairy fermentation and their corresponding technological and probiotic-associated roles are summarized in Table 2.

Table 2. Metabolic activities of lactic acid bacteria and their functional roles in fermented dairy products.

Activity	**Main products**	**Role in fermented dairy products**	**Probiotic-associated relevance**
Lactose fermentation	Lactic acid	Reduces pH, promotes preservation, supports protein coagulation	Inhibits pathogens and spoilage organisms
Proteolysis	Peptides, amino acids	Contributes to flavour development and nutritional modification	May generate potentially bioactive peptides
Exopolysaccharide production	Polysaccharides	Improves viscosity, texture, and water retention	May enhance stress protection and host interaction
Bacteriocin production	Antimicrobial peptides	Improves food safety and microbiological stability	Supports antagonistic activity against undesirable microorganisms
Flavour and aroma	Diacetyl,	Enhances sensory	Indirectly supports regular

metabolism	acetaldehyde, acetoin, other aroma compounds	quality and product acceptability	consumption of functional fermented foods

4. Stress Adaptation and Survival

For lactic acid bacteria (LAB) to exert probiotic-associated effects after consumption, they must survive passage through the gastrointestinal tract, where they are exposed first to gastric acidity and then to bile salts in the small intestine. Gastric acid can reduce intracellular pH, denature proteins, and disrupt essential metabolic processes, whereas bile salts act as detergents that damage cell membranes and can also trigger protein and DNA stress. Survival under these conditions is therefore a major functional requirement for LAB intended for probiotic use. Reviews on probiotic mechanisms and fermented dairy functionality consistently treat acid and bile tolerance as key selection criteria for candidate strains.

LAB use several acid tolerance systems to maintain viability in low-pH environments. One important mechanism is the F0F1-ATPase proton pump, which expels excess protons from the cytoplasm and helps maintain intracellular pH homeostasis. In addition, acid stress responses involve the synthesis of stress proteins and chaperones that protect or refold damaged proteins, as well as broader adjustments in cellular metabolism that reduce acid-induced injury. These responses are strain-dependent, which is why tolerance observed in one LAB strain cannot be assumed for another, even within the same species. Bile tolerance depends on a partly different set of mechanisms. Because bile salts disrupt membrane integrity, LAB often respond through changes in membrane composition, including altered fatty acid profiles and surface-associated structures that reduce membrane damage. Another important mechanism is bile salt hydrolase (BSH) activity, which deconjugates bile salts and may decrease their toxicity for some strains. Reviews of bile resistance in lactobacilli also describe transport systems, proton or solute efflux, and protein quality-control pathways as part of the adaptive response to bile exposure.

The food matrix also matters. Fermented dairy products can improve LAB survival during gastrointestinal transit because milk proteins, fat, and the viscous fermented structure may buffer acidity and provide physical protection against harsh digestive conditions. This protective effect does not replace intrinsic stress tolerance, but it can enhance survival compared with delivery in less protective matrices. These adaptations are critical for the transition from a food-associated environment to the gastrointestinal tract.

5. Linking Metabolism to Probiotic Functionality

The metabolic activity of lactic acid bacteria (LAB) is closely linked to the probiotic-associated properties often attributed to fermented dairy products. These links are not theoretical. They arise from specific biochemical processes that affect microbial survival, pathogen inhibition, digestion-related functions, and possible interactions with the host environment. In this context, metabolism provides the mechanistic basis for understanding why some LAB strains are functionally relevant beyond their role in fermentation [8,9]. One of the clearest examples is the relationship between acid production, bacteriocin synthesis, and antimicrobial activity. During fermentation, LAB convert lactose into lactic acid, causing a reduction in pH that inhibits many spoilage organisms and pathogenic bacteria [4,5]. In some strains, this effect is reinforced by the production of bacteriocins and other antimicrobial metabolites, which further suppress competing microorganisms [20,21]. Together, acidification and antimicrobial peptide production contribute not only to food preservation but also to one of the main probiotic-associated traits of LAB, namely antagonism against undesirable microbes [7,8].

LAB metabolism may also support digestion-related functions. Their enzymatic activities, including carbohydrate metabolism and proteolysis, contribute to the breakdown of milk components and the release of smaller peptides and metabolites [11,14]. This can improve the digestibility of fermented dairy products and may support lactose utilization in individuals with reduced lactase activity, particularly when viable cultures remain active in the product [3,9]. In addition, peptides generated during fermentation have been studied for potential bioactive properties, although these effects should be interpreted cautiously unless confirmed in vivo [16]. Exopolysaccharide (EPS) production represents another important link between metabolism and probiotic functionality. EPS can improve product texture, but it may also support bacterial persistence by protecting cells against environmental stress and by influencing surface interactions [17,18]. Some studies have suggested roles for EPS in adhesion and host interaction, although these effects depend heavily on polymer structure and strain background [18,19]. Similarly, stress adaptation mechanisms such as acid resistance, membrane remodeling, and bile salt hydrolase activity improve the likelihood that LAB survive transit through the gastrointestinal tract [22,23].

These adaptations are central to probiotic performance because survival is a prerequisite for any downstream effect. However, probiotic functionality is strain-specific and cannot be generalized across all lactic acid bacteria. The presence of a LAB species in a fermented dairy product does not by itself guarantee antimicrobial activity, gastrointestinal survival, or measurable health benefit. Functional interpretation must therefore be based on strain-level evidence, metabolic characteristics, and, ideally, validation beyond in vitro assays [8,24].

6. Future Perspectives

Future research on LAB in traditional fermented dairy products should move beyond genus- or species-level description and focus more consistently on strain-level analysis. Closely related strains may differ substantially in acidification rate, exopolysaccharide production, bacteriocin synthesis, stress tolerance, and host-related functional traits. For this reason, taxonomic identification alone is not sufficient to predict technological or probiotic value [7,8].

A stronger integration of genomics and metabolomics is also needed. Genomic data can identify genes involved in carbohydrate utilization, proteolysis, bacteriocin production, and bile resistance, while metabolomic approaches can show which compounds are actually produced under fermentation conditions. Together, these tools would provide a more precise understanding of how LAB function in real food systems rather than only under simplified laboratory conditions [10,18].

Traditional dairy products remain especially important because many of them are still underexplored microbial ecosystems. Products such as qatiq, suzma, chakki, chalob, and qurtob may contain locally adapted LAB strains with valuable technological and functional characteristics that are not represented in commercial starter cultures [1,2]. However, promising in vitro results should not be overinterpreted. More in vivo validation is needed to determine whether metabolic traits observed during fermentation or laboratory testing translate into consistent health-related effects in the host [8,9].

7. Conclusion

Lactic acid bacteria are central to the transformation of milk into fermented dairy products because their metabolism drives the main biochemical changes that define these foods. Through carbohydrate fermentation, LAB acidify the dairy matrix and promote preservation. Through proteolysis, exopolysaccharide production, antimicrobial compound synthesis, and flavour metabolism, they contribute to texture, safety, and sensory quality [10,11,15,17,20]. In this sense, fermentation outcomes are direct consequences of microbial metabolic activity rather than the simple presence of bacteria. The same metabolic processes also explain why certain LAB strains may show probiotic-associated potential. Acid and bacteriocin production can inhibit undesirable microorganisms, enzymatic activity can support digestion-related functions, EPS may contribute to protection and interaction, and stress adaptation mechanisms can improve survival under gastrointestinal conditions [8,18,22]. However, these functional traits are not universal. Their expression depends on the individual strain, the food matrix, and the conditions under which fermentation and consumption occur [8,24]. Traditional fermented dairy products are therefore valuable not only as foods but also as reservoirs of metabolically diverse LAB with possible technological and probiotic applications. At the same time, more rigorous strain-level characterization, integrated omics approaches, and in vivo studies are needed to distinguish genuine functional potential from broad generalization. A clearer understanding of LAB metabolism will strengthen both the scientific evaluation of traditional dairy microbiota and the future development of functional fermented foods [1,7,10].

References

1. Konuspayeva G, Baubekova A, Akhmetsadykova S, Faye B. Traditional dairy fermented products in Central Asia. Int Dairy J. 2023;137:105514.
2. Wang D, Zhang L, Zhang Y, Xu H, Liu W. Isolation and identification of lactic acid bacteria from traditional dairy products in Baotou and Bayannur of midwestern Inner Mongolia and q-PCR analysis of predominant species. Korean J Food Sci Anim Resour. 2016;36(4):499-507.

3. Rahman A, Akter M, Islam MS, Rahman A, Biswas L, Asaduzzaman M. Lactic acid bacteria and their beneficial effects in fermented dairy products. J Sher-e-Bangla Agric Univ. 2022;13(1-2):19-29.
4. Ahansaz N, Tarrah A, Teglia C, Corredig M, Ibrahim SA. Lactic acid bacteria in dairy foods: prime sources of antimicrobial compounds. Fermentation. 2023;9(11):964.
5. Dobreva L, Borisova D, Paunova-Krasteva T, Dimitrova PD, Hubenov V, Atanasova N, et al. From traditional dairy product “Katak” to beneficial Lactiplantibacillus plantarum strains. Microorganisms. 2023;11(12):2847.
6. Sionek B, Szydłowska A, Küçükgöz K, Kołożyn-Krajewska D. Traditional and new microorganisms in lactic acid fermentation of food. Fermentation. 2023;9(12):1019.
7. Guo ZH, Wang Q, Zhao JH, Xu YP, Mu GQ, Zhu XM. Lactic acid bacteria with probiotic characteristics in fermented dairy products reduce cow milk allergy. Food Biosci. 2023;55:103055.
8. Ghosh T, Beniwal A, Semwal A, Navani NK. Mechanistic insights into probiotic properties of lactic acid bacteria associated with ethnic fermented dairy products. Front Microbiol. 2019;10:502.
9. Widyastuti Y, Febrisiantosa A, Tidona F. Health-promoting properties of lactobacilli in fermented dairy products. Front Microbiol. 2021;12:673890.
10. Sharma H, Ozogul F, Bartkiene E, Rocha JM. Impact of lactic acid bacteria and their metabolites on the techno-functional properties and health benefits of fermented dairy products. Crit Rev Food Sci Nutr. 2023;63(21):4819-4841.
11. Savijoki K, Ingmer H, Varmanen P. Proteolytic systems of lactic acid bacteria. Appl Microbiol Biotechnol. 2006;71(4):394-406.
12. Akpoghelie PO, Edo GI, Mafe AN, Isoje EF, Igbuku UA, Ali ABM, et al. Food, health, and environmental impact of lactic acid bacteria: the

superbacteria for posterity. Probiotics Antimicrob Proteins. 2025;17(5):2819-2855.

13. Nagaoka S. Yogurt production. Methods Mol Biol. 2019;1887:45-54.
14. Kunji ERS, Mierau I, Hagting A, Poolman B, Konings WN. The proteolytic systems of lactic acid bacteria. Antonie Van Leeuwenhoek. 1996;70(2-4):187-221.
15. Smid EJ, Kleerebezem M. Production of aroma compounds in lactic fermentations. Annu Rev Food Sci Technol. 2014;5:313-326.
16. Meisel H, Bockelmann W. Bioactive peptides encrypted in milk proteins: proteolytic activation and tropho-functional properties. Antonie Van Leeuwenhoek. 1999;76(1-4):207-215.
17. Ruas-Madiedo P, Hugenholtz J, Zoon P. An overview of the functionality of exopolysaccharides produced by lactic acid bacteria. Int Dairy J. 2002;12(2-3):163-171.
18. Prete R, Alam MK, Perpetuini G, Perla C, Pittia P, Corsetti A. Lactic acid bacteria exopolysaccharides producers: a sustainable tool for functional foods. Foods. 2021;10(7):1653.
19. Daba GM, Elnahas MO, Elkhateeb WA. Contributions of exopolysaccharides from lactic acid bacteria as biotechnological tools in food, pharmaceutical, and medical applications. Int J Biol Macromol. 2021;173:79-89.
20. O'Sullivan L, Ross RP, Hill C. Potential of bacteriocin-producing lactic acid bacteria for improvements in food safety and quality. Biochimie. 2002;84(5-6):593-604.
21. Silva CCG, Silva SPM, Ribeiro SC. Application of bacteriocins and protective cultures in dairy food preservation. Front Microbiol. 2018;9:594.
22. Ruiz L, Margolles A, Sánchez B. Bile resistance mechanisms in Lactobacillus and Bifidobacterium. Front Microbiol. 2013;4:396.

23. Horáčková Š, Plocková M, Demnerová K. Importance of microbial defence systems to bile salts and mechanisms of serum cholesterol reduction. Biotechnol Adv. 2018;36(3):682-690.
24. Amund OD. Exploring the relationship between exposure to technological and gastrointestinal stress and probiotic functional properties of lactobacilli and bifidobacteria. Can J Microbiol. 2016;62(9):715-725.
25. Gao X, Qiao S, Muhammad I, Jiao C, Han J, Liu M. Lactobacillus, Bifidobacterium and Lactococcus response to environmental stress: mechanisms and application of cross-protection to improve resistance against freeze-drying. J Appl Microbiol. 2022;132(2):802-821.
26. Heidebach T, Först P, Kulozik U. Microencapsulation of probiotic cells for food applications. Crit Rev Food Sci Nutr. 2012;52(4):291-311.