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# From fermentation to function: The hidden antioxidants inside fermented milks

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**ABSTRACT**

**Objective**: To perform a literature review on antioxidant compounds present in fermented milks, highlighting their potential role in mitigating oxidative stress.

**Design/methodology/approach**: This review analyzes scientific literature addressing the antioxidant components of fermented milks, including native milk constituents, microbial metabolites, and bio-transformed compounds generated during fermentation.

**Results**: Fermented milks contain a wide spectrum of antioxidant compounds arising from milk components, microbial metabolism, and LAB-mediated bio-transformations. These compounds collectively contribute to scavenging free radicals and reducing reactive oxygen species (ROS).

**Limitations on study/implications**: Further *in vivo* studies and clinical evidence are needed to substantiate health claims and clarify dose-response relationships.

**Findings/conclusions**: The available evidence supports fermented milks as promising functional foods with substantial antioxidant potential. Their regular consumption may contribute to protection against oxidative stress-related damage and associated chronic degenerative diseases, positioning fermented milks as a potential first line of dietary defense.

**Keywords**: Fermented milks; antioxidants; lactic acid bacteria; probiotics; oxidative stress; functional foods.

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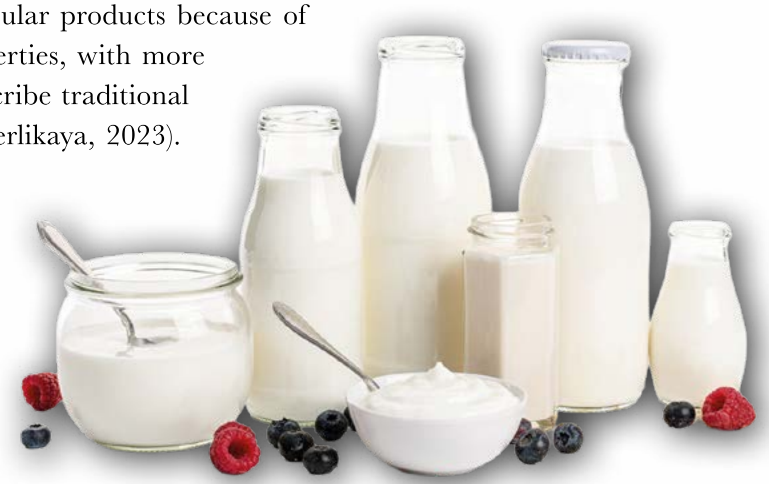
## INTRODUCTION

Fermentation is the oldest biotechnological method used to extend the shelf life of milk and has been practiced for myriads of years across diverse cultures (Hill *et al.*, 2017). Nowadays, fermented milks are consumed worldwide and are very popular products because of their distintive sensory properties, with more than 400 names used to describe traditional and commercial varieties (Yerlikaya, 2023). Beyond their cultural and gastronomic importance, these fermented foods have played a significant role in human nutrition, serving as sources of energy and nutrients



and being associated with health-promoting effects since medieval times (Hill *et al.*, 2017; Yerlikaya, 2023).

Early production of fermented milk relied on spontaneous fermentation by native microflora present in raw milk. In contrast, present methods use selected starter cultures, allowing control over fermentation parameters and consistent product quality. These starter cultures contribute to food safety and influence sensory, technological, nutritional, and health-related properties of the final product (Bintsis & Papademas, 2022).

At biochemical level, lactic acid bacteria (LAB) play multiple essential roles in fermented milks, contributing to both product quality and nutritional value. They are primarily responsible for the production of lactic acid and various antimicrobial compounds, which enhance preservation and microbiological safety (Sharma *et al.*, 2023; Yerlikaya, 2023). In addition, LAB synthesize key flavor compounds, such as acetaldehyde, that are characteristic of fermented dairy products. These microorganisms also produce exopolysaccharides, which improve texture and mouthfeel. In addition, fermentation promotes changes in lipid fractions, mineral bioavailability, and the stability and synthesis of vitamins. Collectively, these activities lead to an overall improvement of the nutritional value of fermented milks (Anumudu *et al.*, 2024).

The health benefits of fermented milks arise from the biologically active components naturally present in milk, the metabolites produced and those biotransformed by LAB during fermentation, resulting in a biogenic effect that enhances the functional value of these products (Sharma *et al.*, 2023). During fermentation, microorganimsms drive complex biochemical transformations, including lactose fermentation and proteolysis of milk proteins, leading to the release of peptides, free amino acids, and other low-molecular-weight compounds with potential biological activity. In addition to generating beneficial compounds, certain LAB strains (probiotics) exert direct effects on the host, including improved lactose digestion, modulation of immune responses, maintenance of gut microbiota balance, reduction of serum cholesterol levels, among others (Gao *et al.*, 2025; Kaur *et al.*, 2022). More recently, several LAB strains have also been shown to possess intrinsic bioactive propesties, further expanding their significance as functional microorganisms and reinforcing the potential of fermented milks as health-promoting foods (Bryukhanov *et al.*, 2022).

The scientific interest in the health effects of fermented milk dates back to the early 20$^{th}$ century, when Metchnikoff proposed that the consumption of yogurt containing LAB could positively influence gut microbiota composition, contributing to improved intestinal health and longevity (Bintsis & Papademas, 2022). These early hypotheses placed the foundation for contemporary research exploring the biochemical and physiological mechanisms through which fermented milks exert health-promoting effects, including their antioxidant benefits.

On the other hand, oxidative stress is recognized as a key factor in the development of various diet-related chronic diseases, underlining the importance of dietary antioxidant as a key nutritional property of foods (Fardet & Rock, 2018). In this sense, it has been reported that fermented milks exhibited antioxidant activity, which is attributed to multiple biomolecules, including the release of antioxidant peptides during protein hydrolysis and the formation of microbial metabolites with redox activity (*e.g.* vitamins, exopolysaccharides). These antioxidant properties not only add functional value to fermented dairy products but also position them as promising dietary components for promoting overall health.

**Antioxidants and Their Relevance in Fermented Milks**

Antioxidants are molecules capable of preventing or reducing oxidative damage caused by reactive oxygen species (ROS). Epidemiological evidence suggest that an adequate consumption of dietary antioxidants may contribute to the prevention of chronic diseases such as cancer, cardiovascular disorders, and neurodegenerative conditions (Muscolo *et al.*, 2024). ROS can react with lipids, proteins, and DNA, generating cellular damage that contributes to disease progression; however, it is important to note that certain reactive species also play essential physiological roles in cell signaling and immune responses (Sies *et al.*, 2022).

Diet plays a crucial role in modulating oxidative stress and maintaining redox homeostasis (Zujko & Witkowska, 2023). In this sense, antioxidant-rich foods, including fermented milks, as key components of a health-promoting diet. Beyond supplying essential nutrients, dietary patterns influence the balance between pro-oxidant and antioxidant processes, thereby affecting the capacity of biological systems to counteract free radical generation. Fermented milks, in particular, have attracted growing attention because their fermentation process enhances the bioavailability and bioactivity of antioxidant compounds naturally present in milk. Lactic acid bacteria not only preserve nutritional quality but can release bioactive peptides, synthesize antioxidant metabolites, and modulate host antioxidant defenses. As a result, the regular consumption of fermented dairy products may contribute to mitigating oxidative damage, supporting immune function, and promoting overall metabolic resilience, thereby reinforcing their potential role in the prevention of oxidative stress-related disorders and in the promotion of overall health (Stobiecka *et al.*, 2022).

**Native Milk Constituents as Sources of Antioxidants**

Milk and dairy products naturally contain a diverse array of antioxidant systems that contribute to their capacity to counteract oxidative stress. Among these, enzymatic antioxdiants including superoxide dismutase (SOD), catalase, and glutathione peroxidase, which play an important role in protecting against oxidative damage. Although the activity of these enzymes may be partially reduced during processing, a fraction remains functional in the final products (Khan *et al.*, 2019; Stobiecka *et al.*, 2022). Moreover, during fermentation, their antioxidant capacity may be complemented or enhanced by microbial enzymes produced by lactic acid bacteria, thereby contributing to the overall antioxidant potential of fermented dairy products (Khan *et al.*, 2019).

Beyond enzymatic defenses, milk and dairy products contain a wide range of non-enzymatic antioxidants that contribute significantly to their overall antioxidant capacity. Fat-soluble vitamins such as vitamins A and E play a crucial role in protecting milk lipids from peroxidation, while water-soluble vitamin C contributes to the scavenging of aqueous-phase free radicals and the regeneration of other antioxidants. In addition, carotenoids present in milk fat exhibit potent antioxidant activity and may also contribute to anti-inflammatory effects. Conjugated linoleic acid (CLA), a bioactive lipid found in dairy fat, has been reported to exert antioxidant effects through modulation of oxidative pathways and lipid metabolism (Khan *et al.*, 2019; Zaitsev, 2025). Reduced glutathione (GSH) represents another key component of the milk antioxidant system, acting both as a direct scavenger of reactive species and as a substrate for glutathione peroxidase, thereby maintaining cellular redox homeostasis. Furthermore, essential trace minerals such as zinc and selenium contribute indirectly to antioxidant defense by serving as structural or catalytic cofactors for antioxidant enzymes, including SOD and glutathione peroxidase (Zaitsev, 2025).

Collectively, these native milk constituents form a multifaceted antioxidant network that provides a biochemical foundation for the antioxidant properties of fermented dairy products. When combined with fermentation-derived bioactive compounds and LAB-mediated metabolic activities, these intrinsic antioxidants substantially enhance the functional value of fermented milks as dietary sources of redox-active components.

**Microbial-Derived Antioxidant Metabolites in Fermented Dairy Products**

Traditionally, dietary proteins have been regarded as sources of energy and essential amino acids. However, accumulating evidence indicates that milk proteins also contain encrypted bioactive peptides that exert physiological functions in cardiovascular, immune, digestive, and nervous systems. These peptides are inactive within the parent proteins and are released during fermentation, storage, ripening, or gastrointestinal digestion (Auestad & Layman, 2021; Chourasia *et al.*, 2021).

Fermented dairy products, including yogurt, kefir, sour milk, and other LAB-fermented milks, are recognized as important sources of antioxidant peptides. During fermentation, LAB proteolytic systems cleave caseins and whey proteins, generating low-molecular-weight peptides with antioxidant potential. he antioxidant activity of these peptides is strongly dependent on their amino acid composition and sequence, particularly the presence of residues such as histidine, tyrosine, cysteine, and methionine, which contribute to free radical scavenging, proton donation, and metal ion chelation. In addition, peptide hydrophobicity, molecular size, and overall structural conformation play critical roles in determining their effectiveness as antioxidants (Peres Fabbri *et al.*, 2024; Wróblewska *et al.*, 2023).

Beyond fermentation, the antioxidant potential of fermented dairy products may be further enhanced during gastrointestinal digestion. Digestive enzymes such as pepsin, trypsin, chymotrypsin, and brush-border peptidases can release additional antioxidant peptides from both native milk proteins and fermentation-derived peptides. This sequential hydrolysis increases peptide bioaccessibility and may amplify their capacity to neutralize reactive oxygen species, chelate pro-oxidant metal ions, and inhibit lipid peroxidation, thereby extending the functional relevance of fermented milks beyond the food matrix (Quintieri *et al.*, 2024; Singh & Gaur, 2024).

Several LAB strains are capable of synthesizing or enhancing the bioavailability of antioxidant-related vitamins during milk fermentation, particularly B-group vitamins. Among these, folic acid (vitamin B9) plays a pivotal role in nucleotide biosynthesis and one-carbon metabolism, being essential for DNA synthesis and methylation reactions. Although folate does not act as a direct radical scavenger, it exerts indirect antioxidant effects by regulating homocysteine metabolism, thereby reducing oxidative stress associated with hyperhomocysteinemia (Abdul Hakim *et al*., 2023). Certain LAB strains, such as *Lactobacillus* and *Lactococcus* species, have been reported to synthesize folate during milk fermentation, contributing to the nutritional and functional enhancement of fermented dairy product (Mahara *et al*., 2021). In addition, LAB-mediated production of riboflavin (vitamin B2) and other cofactors involved in redox reactions may further support cellular antioxidant defenses (Zhang *et al*., 2022).

On the other hand, organic acids produced during fermentation, including lactic, acetic, and propionic acids, also contribute indirectly to antioxidant activity. These compounds lower the pH of the dairy matrix, which can inhibit oxidative reactions and enhance the stability of antioxidant peptides and vitamins (Anumudu *et al*., 2024; Erem & Kilic-Akyilmaz, 2024). Moreover, certain organic acids exhibit metal-chelating properties, reducing the availability of pro-oxidant metal ions such as iron and copper, thereby limiting the formation of reactive oxygen species via Fenton-type reactions (Mussio *et al*., 2025).

In contrast, exopolysaccharides synthesized by LAB are high-molecular-weight polymers that play important roles in the technological properties of fermented milks, such as viscosity and texture. Beyond these functions, EPS have been increasingly recognized for their biological activities, including antioxidant effects (Jurášková *et al*., 2025; Zhang *et al*., 2025). LAB-derived EPS can scavenge free radicals, chelate metal ions, and modulate cellular antioxidant pathways. Their antioxidant capacity is influenced by monosaccharide composition, molecular weight, and branching degree, as well as by fermentation conditions and bacterial strain specificity (Hernández-Figueroa *et al*., 2025; Zhang *et al*., 2023).

Collectively, the generation of antioxidant peptides and microbial-derived metabolites during fermentation underscores the importance of LAB strain selection and fermentation conditions in maximizing the antioxidant potential of dairy products. Understanding these microbial-driven biochemical processes is essential for the rational design of fermented milks with enhanced functional and health-promoting properties.

**Bio-Transformed Antioxidant Compounds Generated During Fermentation**

Although milk itself is not a primary source of phytochemicals, fermented milks can act as effective carriers and transformation matrices for phytochemicals introduced through plant-derived ingredients, such as fruits, cereals, legumes, herbs, or plant extracts. During fermentation, lactic acid bacteria (LAB) mediate the bio-transformation of these phytochemicals through enzymatic and metabolic activities, often enhancing their bioavailability and antioxidant capacity (Dixit *et al*., 2023; Wróblewska *et al*., 2023).

Polyphenols, including phenolic acids, flavonoids, and tannins, are among the most extensively bio-transformed phytochemicals in fermented milks. LAB enzymes such as $\beta$-glucosidases, esterases, and phenolic acid decarboxylases hydrolyze glycosylated or polymeric phenolic into simpler aglycone forms, which generally exhibit higher antioxidant activity and improved intestinal absorption. Similarly, bound phenolic compounds can be released from plant matrices during fermentation, increasing their functional efficacy (Dissanayake *et al.*, 2025; Kumar *et al.*, 2025).

Other phytochemicals, such as carotenoids and phytosterols, may undergo structural modifications during fermentation that improve their stability or bioaccessibility within the dairy matrix (Dissanayake *et al.*, 2025; Kanimozhi & Sukumar, 2025; Kumar *et al.*, 2025). LAB metabolism can also reduce molecular complexity or alter redox properties, contributing to enhanced radical-scavenging or metal-chelating activity (Arslan *et al.*, 2025; Mussio *et al.*, 2025). Additionally, interactions between phytochemicals and milk proteins or peptides generated during fermentation can protect these compounds from degradation and modulate their release during digestion (Fitsum *et al.*, 2025; Kumar *et al.*, 2025).

Overall, the bio-transformation of phytochemicals in fermented milks is driven by LAB enzymatic activity, changes in pH, and matrix interactions, resulting in fermented dairy products with improved antioxidant potential and functional properties. This highlights the relevance of fermented milks as versatile platforms for delivering bioactive plant compounds and developing innovative functional foods.

## CONCLUSIONS

Fermented milks are valuable functional foods containing natural and microbial derived antioxidant compounds. LAB contribute to antioxidant activity through production of bioactive metabolites, release of peptides, synthesis of vitamins such as folate, and the intrinsic antioxidant properties of their cells and intracellular components. Although a substantial body of *in vitro* research demonstrates strong antioxidant potential, more in vivo studies are required to fully understand the mechanisms and health implications. Given their global consumption, sensory acceptability, and proven functional properties, fermented milks represent a promising dietary strategy for mitigating oxidative stress and promoting human health.

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