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Targeted dairy fortification: leveraging bioactive compounds to enhance nutritional value

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ABSTRACT

Dairy products, rich in nutrients, are crucial for human health and disease prevention. Recent trends focus on enhancing their nutritional value by fortifying them with bioactive compounds from plant and animal sources. Scientific evidence suggests these compounds can improve public health by potentially treating and preventing diseases, including cancer. This systematic review discusses advances in dairy product fortification with health-promoting compounds, highlighting their role in correcting nutritional deficiencies and reducing chronic disease risk. Innovative delivery systems are being developed to improve the stability and functionality of these compounds in fortified dairy products. Despite challenges in maintaining the physical, textural, and sensory qualities of dairy products, fortification is a promising public health strategy. The review calls for interdisciplinary research to better understand the bioavailability, effectiveness, and long-term health impacts of bioactive compounds in dairy foods. Such research could inform best practices and policy recommendations. Using dairy products as carriers for bioactive compounds can significantly improve nutritional status and reduce the global burden of chronic diseases, making it a strategic approach to public health nutrition. This review cautiously evaluates current evidence, particularly regarding chronic disease prevention, and emphasizes the need for further research on specific populations, such as children and the elderly.

KEYWORDS

Bioactive compounds; bioavailability; chronic disease prevention; consumer acceptance; dairy fortification; public health

Introduction

In pursuing enhanced public health and nutritional security, dairy foods play a central role in the diets of millions globally. Known for their rich composition of essential nutrients, including proteins, vitamins, and minerals, dairy products are not just staple foods but also crucial in achieving balanced diets across various cultures and age groups (World Health Organization 2006). Despite their nutritional benefits, a global challenge of nutritional deficiencies exists that can lead to a range of health issues, from simple vitamin deficiencies to complex chronic conditions impacting the quality of life. Addressing these nutritional gaps through traditional means of dietary diversification and supplementation has limitations, especially in regions where access to a diverse variety of foods is limited by economic, environmental, or cultural factors (Park 2009).

Bioactive compounds, such as vitamins, minerals, antioxidants, and omega-3 fatty acids, can address nutritional deficiencies and reduce the risk of chronic diseases when added to foods. This process not only appeals to the health-conscious consumers but it also offers economic benefits by potentially reducing healthcare costs. The significance of bioactive compounds in food fortification lies in their ability to enhance the nutritional value of foods, contribute to disease prevention, improve immune function, offer mental health benefits, and provide targeted nutrition to specific population groups. However, fortifying foods with bioactive compounds requires careful scientific evaluation and monitoring to ensure safety and effectiveness (Martins, Oliveira, and Ferreira 2018).

The fortification of dairy foods with bioactive compounds represents a strategic approach to enhancing the nutritional profile of a widely consumed food category, thereby contributing significantly to overall nutrition. Dairy products, inherently rich in essential nutrients such as calcium, vitamin D, and proteins, serve as an ideal matrix for the incorporation of additional bioactive compounds, including vitamins, minerals, omega-3 fatty acids, and plant-derived antioxidants. This fortification process aims to address nutritional deficiencies and promote the intake of compounds beneficial for health that are otherwise lacking in the average diet (Lawrence and Lawrence 2013; Preedy, Srirajaskanthan, and Patel 2013).

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Targeted nutrition for various population groups, including children, the elderly, and those with specific dietary restrictions, is essential for addressing unique health requirements. Such nutritional interventions offer beneficial options for the consumers while having the potential for broader economic benefits by potentially reducing healthcare costs associated with nutritional deficiencies and chronic diseases. Ensuring these enhancements are scientifically backed and accessible to intended populations is vital for their success and impact on public health and well-being. (Ali et al. 2022).

While existing literature has touched upon the fortification of dairy foods with bioactive compounds, there remains a noticeable absence of a contemporary, systematic, and comprehensive review that holistically addresses the multifaceted aspects of this research, particularly with a concentrated focus on public health implications. In light of this, the current research bridges this gap. The objective was to delve into the recent advancements in the fortification of dairy foods with bioactive compounds and elucidate their transformative potential in shaping public health outcomes. We provide fresh insights into the types of bioactive compounds for fortification, the range of dairy products that can be enhanced, and the potential health benefits. Innovative delivery technologies are also explored, with a focus on how encapsulation methods (including nanoencapsulation) can support compound stability and functionality, while acknowledging the need to balance technological feasibility with consumer acceptability. We also address the technical challenges and innovations in the fortification process, regulatory and ethical considerations, and the need for more research. This article highlights the importance of dairy food fortification as a strategy for improving public health. Additionally, we emphasize the need for interdisciplinary research to explore the bioavailability, effectiveness, and long-term health implications of bioactive compounds in dairy foods, while moderating strong health claims based on preliminary evidence.

Methodology

To ensure the methodological rigor of this systematic review, a structured approach was followed to select and evaluate studies related to the fortification of dairy products with bioactive compounds. Inclusion criteria consisted of peer-reviewed articles, meta-analyses, and clinical trials published between 2015 and 2024 that focused on dairy fortification with bioactive compounds, involved human subjects or preclinical models relevant to human health, and addressed mechanisms of action, bioavailability, stability, health benefits, and public health implications. Exclusion criteria included non-peer-reviewed sources, reviews without original data, studies unrelated to dairy fortification, and research conducted exclusively on animal models without clear human health relevance. A comprehensive search was performed across major databases such as PubMed, Scopus, Web of Science, and Google Scholar using specific keywords like "dairy fortification," "bioactive compounds," "nutritional value," "public health," "chronic disease prevention," and "consumer acceptance." Titles, abstracts, and full texts were systematically screened to align with the review's objectives.

The quality of the selected studies was critically evaluated based on sample size and representativeness, study design (including randomized controlled trials, observational studies, and experimental models), relevance to real-world public health concerns, and acknowledgment of limitations such as small sample sizes, short study durations, or reliance on preclinical data. This systematic approach ensures robust and well-supported evidence reflective of current scientific knowledge while highlighting gaps in the literature. By explicitly defining inclusion and exclusion criteria, the review enhances transparency and reproducibility, enabling readers to understand how studies were chosen and evaluated.

An overview of bioactive compounds

Definition and classification of bioactive compounds

A bioactive compound is defined as any substance present in food, animals, or plants that influences the body that consumes it. These compounds, often integrated into foods as bioactive or functional ingredients, enhance health when consumed. They can be naturally occurring in common foods, added as supplements (like probiotics and antioxidants), or fortified (such as prebiotics) (Banwo et al. 2021). Unlike food additives, which are used to modify taste or appearance, bioactive ingredients retain their health-promoting properties even after extraction from their original sources and are not merely sensory enhancers. The definition of bioactive compounds often excludes essential nutrients, focusing instead on non-nutritive constituents in foods that provide health benefits beyond basic nutritional value. These compounds can be derived from food sources or inedible origins and are used extensively in non-nutritional contexts to enhance health by modifying physiological functions or improving biological activity (Campos 2018; Suleria and Barrow 2019).

Key bioactive ingredients include a wide range of substances like prebiotics, probiotics, amino acids, omega-3 fatty acids, phytochemicals, vitamins, and minerals. These ingredients are sourced from various foods and are used in products ranging from functional foods and beverages to supplements and personal care items. Bioactive components from marine sources such as chitosan and astaxanthin, particularly from macroalgae and fish waste, show promise due to their significant health benefits like anti-inflammatory and anticancer properties. Understanding the characteristics of bioactive ingredients is crucial for their application across different industries (Stoica et al. 2023).

The concept of bioavailability is critical in this context, referring to how well these ingredients are absorbed and utilized in the body. It encompasses factors like absorption, metabolism, and the physiological barriers that affect their efficacy. Current knowledge about the optimal levels of these compounds necessary for health benefits remains limited. While bioactive compounds typically come from plants and are part of the food chain, they can also be sourced from non-food materials, including waste products. Research is expanding into the use of bioactive compounds from various organisms, including marine and terrestrial microorganisms, which produce secondary metabolites with potential health benefits (Atef and Ojagh 2017). Despite their varied sources, the core principle of bioactive compounds is their capacity to influence health in beneficial ways. This excludes any adverse effects such as toxicity or allergenicity. Definitions of bioactive compounds continue to evolve, reflecting their broad application and the ongoing discovery of their roles in health and disease prevention. This ongoing evolution underscores the importance of understanding and utilizing bioactive compounds to enhance human health through diet and other means (Gupta et al. 2015).

The classification of bioactive compounds is generally based on their chemical structure and biological function. Major classes include polyphenols, peptides, terpenoids, glucosinolates, and alkaloids (Table 1). Each class encompasses a variety of compounds characterized by distinct molecular frameworks and specific health-promoting attributes. For instance, polyphenols, which include flavonoids and phenolic acids, are celebrated for their antioxidant properties and their role in the prevention of cardiovascular diseases and cancer. On the other hand, peptides have been noted for their role in regulating blood pressure and anti-inflammatory properties (Walia, Gupta, and Sharma 2019).

Bioactive compounds are further categorized based on their source and their specific effects. For example, phytochemicals refer to bioactive compounds derived from plants, while zoochemicals originate from animal sources. The exploration of marine bioactive compounds has also gained attention due to the unique and potent biological activities exhibited by marine-derived substances, which include anti-inflammatory, antitumor, and antibiotic effects (Zou et al. 2023). The ongoing study and classification of bioactive compounds are critical for several reasons. Firstly, understanding their classification helps systematically explore their potential health benefits. Secondly, it assists in identifying sources rich in specific bioactive compounds, facilitating targeted dietary recommendations, and the development of functional foods. Lastly, the classification and characterization of bioactive compounds are essential for their incorporation into medicinal and therapeutic products, providing a foundation for further pharmaceutical development and clinical applications (Rashmi and Negi 2020). Moreover, understanding their classification aids in addressing challenges such as preserving their stability during processing, ensuring their bioavailability, and moderating claims regarding their health benefits based on current evidence.

Sources of bioactive compounds

Bioactive compounds, crucial for enhancing health and preventing diseases, are derived from various natural and synthetic sources, as detailed in Table 2. Predominantly, plants offer a rich array of compounds, such as flavonoids and carotenoids found in fruits and vegetables. These are influenced by factors like soil type, sunlight, and rainfall, which affect their phytochemical content and composition. Similarly, the marine environment contributes unique bioactives, including omega-3 fatty acids and astaxanthin from fish and algae, recognized for their anti-inflammatory, antioxidant, and anticancer properties (Bernhoft 2010; Christaki et al. 2012). Recent advancements in encapsulation techniques, such as nanoencapsulation, have enhanced the stability and bioavailability of marine-derived bioactives like omega-3 fatty acids, making them more effective in fortified dairy products (Hosseini, Ramezanzade, and McClements 2021).

Table 1. Classification and characteristics of major bioactive compounds.

Class	Examples	Source	Primary biological effect	References
Polyphenols	Flavonoids, phenolic acids	Berries, nuts	Antioxidant, anti-inflammatory	Câmara et al. (2020)
Peptides	Casein peptides, gluten exorphins	Dairy, wheat	Antihypertensive, opioid effects	Sánchez and Vázquez (2017)
Terpenoids	Limonene, taxol	Citrus fruits, yew trees	Anticancer, immune modulation	Masyita et al. (2022)
Glucosinolates	Sulforaphane, Glucobrassicin	Broccoli, kale	Anticancer, detoxification	Bischoff (2021)
Alkaloids	Caffeine, nicotine	Coffee beans, tobacco	Stimulant, neuroactive	Gracz-Bernaciak, Mazur, and Nawrot (2021)
Saponins	Ginsenosides, Quillaja saponins	Ginseng, soapbark tree	Immune booster, anticholesterol	Nguyen et al. (2020)
Polysaccharides	Beta-glucans, chitosan	Oats, mushrooms, shellfish	Immune modulation, antioxidant, anti-inflammatory	Smestad Paulsen (2002)

Table 2. Sources of bioactive compounds and their health benefits.

Source type	Examples of sources	Bioactive compounds	Health benefits	References
Plants	Fruits, vegetables, nuts, grains	Flavonoids, carotenoids, phenolics, pectin, fucoidan	Antioxidant properties, anti-inflammatory, hypoglycemic, hypolipidemic, immune activation	Bernhoft (2010)
Marine	Fish, algae, Crustaceans	Omega-3 fatty acids, astaxanthin, fucoidan	Heart health, anti-inflammatory, anticancer, immune modulation	Ameen, AlNadhari, and Al-Homaidan. (2021)
Animals	Dairy, Eggs, Meat	Conjugated linoleic acid, lactoferrin	Immune support, fat reduction	Dixit et al. (2023)
Microbes	Bacteria, Yeasts	Probiotics, antibiotics	Gut health, disease prevention	Singh et al. (2017)
Fungi	Mushrooms	Polysaccharides, beta-glucans	Immune enhancement, cholesterol management	Ślusarczyk, Adamska, and Czerwik-Marcinkowska. (2021)
Synthetic	Laboratory	Resveratrol, vitamins	Antioxidant properties, nutritional supplementation	Nieto et al. (2023)
Waste products	Citrus peels, husks	Pectin, dietary fibers	Digestive health, nutrient recycling	Sagar et al. (2018)

Animals also provide essential bioactives like conjugated linoleic acid (CLA) in dairy and beef, studied for its potential to reduce body fat and increase muscle mass, alongside lactoferrin and immunoglobulins found in milk that support the immune system. Microorganisms offer another source, with antibiotics derived from bacteria and probiotics from fermented foods such as yogurt and kefir that are crucial for gut health (Gilbert and Şenyuva 2009). Fungi are notable for compounds like statins and beta-glucans that manage cholesterol and boost immunity, with mushrooms being a potent source of polysaccharides. Furthermore, herbs and spices like turmeric and cinnamon are not just culinary enhancers but are also rich in bioactive compounds such as curcumin and cinnamaldehyde, which have anti-inflammatory and anti-diabetic effects, respectively (Sinha 2020). Advances in biotechnology also allow the synthesis and extraction of bioactive compounds from both conventional and unconventional sources, including agricultural waste, providing a steady supply of these crucial elements for nutritional and medicinal purposes (Akhavan-Mahdavi and Mahdi Jafari 2024). However, the effectiveness of bioactive compounds depends on their stability during processing and storage, as well as their bioavailability upon consumption. Encapsulation techniques such as spray drying and emulsification have been employed to protect sensitive compounds like omega-3 fatty acids and vitamins, ensuring their efficacy in fortified dairy products (Akbarbaglu et al. 2021).

This extensive exploration delves into the diverse origins and types of bioactive compounds, underscoring their significant role in promoting health and guiding agricultural and food processing practices to preserve their content in food products (Côté et al. 2010). Despite the wide range of sources, careful consideration must be given to the potential variability in the quality and concentration of bioactive compounds, especially when sourced from natural materials, to ensure consistent health benefits and safety.

Mechanisms of action

The mechanisms of action of bioactive compounds multifaceted and context-dependent, influenced by the food matrix, digestive processes, and host physiology. This complexity necessitates an understanding of the dynamic interaction between these compounds and the host's physiology, as well as the implications of sustained intake. Drawing parallels with pharmacodynamics, bioactive compounds should possess well-defined targets and action mechanisms. However, the diverse nature of the food matrix, the multiplicity of mechanisms, and the array of responses introduce several fundamental differences. To identify a potential activity mechanism, it is imperative to consider the intended use of the food, the biomarker that will substantiate this claim, and prior evidence gleaned from current information sources. Upon thoroughly examining these factors, various experimental strategies should be contemplated. These experimental strategies range from selecting preclinical or experimental models to applying techniques like transcriptomics or metabolomics, ensuring a robust understanding of bioactive mechanisms (Machado et al. 2024). Encapsulation technologies, such as nanoencapsulation, further support these studies by improving the stability of sensitive bioactives during experimentation. Additionally, exploring these mechanisms aids in optimizing dietary recommendations and supplement formulations to enhance human health and wellness. As the demand for natural and safe health solutions grows, the role of bioactive compounds becomes increasingly crucial, making their study a focal point in nutrition, pharmacology, and holistic medicine. Understanding these mechanisms paves the way for medical advancements and supports the shift toward preventive healthcare, emphasizing the role of diet and natural substances in maintaining health and well-being. Table 3 provides a comprehensive overview of the various mechanisms through which bioactive compounds affect health (Machado et al. 2024).

Bioactive compounds exert their effects by interacting with specific molecular targets within the body, which include a variety of molecules or cells playing critical roles in physiological processes. This fundamental aspect of their mechanism of action influences cellular and systemic functions and manifests in several ways. Many bioactive compounds function through receptor binding on cell surfaces, either activating or inhibiting normal receptor functions and leading to various cellular responses; for example, phytoestrogens from plants mimic estrogen, impacting reproductive and hormonal functions. Additionally, these compounds can modulate enzyme activity, either inhibiting or enhancing it, thus altering metabolic pathways and potentially leading to therapeutic effects, such as curcumin from turmeric reducing inflammation and pain by inhibiting inflammatory enzymes. Some bioactive compounds affect ion channels crucial for cellular signaling and nerve transmission, influencing nerve function, muscle contraction, and heart rate. Others interact directly with DNA, either protecting it from damage or modulating gene expression, affecting cell growth and differentiation with cancer prevention and treatment implications. Furthermore, bioactive compounds often affect signal transduction pathways, systems of communication that govern cellular responses to external stimuli, which can trigger cell death in cancerous cells or activate immune responses, illustrating their broad impact on cell function and behavior (Machado et al. 2024).

Bioactive compounds significantly influence enzyme activity within the body by either inhibiting or activating various enzymes, thus affecting metabolic pathways. This interaction is crucial in how these compounds contribute to health and disease management. For instance, certain bioactive compounds, like those found in green tea, can inhibit enzymes involved in cancer cell proliferation, thereby offering potential cancer-preventive properties. Conversely, other compounds may activate enzymes that aid in detoxification, enhancing the body's ability to remove toxins and protect against disease. These interactions between bioactive compounds and enzymes underscore their potential in therapeutic applications, making them integral to advancements in medical and nutritional science (Machado et al. 2024).

Bioactive compounds play a critical role in modulating signal transduction pathways within cells, thereby

Table 3. Mechanisms of action of bioactive compounds.

Mechanism category	Description	Examples	Health Implications	References
Molecular targets	Specific molecular interactions that drive biological effects.	Ligands binding to cellular receptors	Different receptors and signaling molecules based on compound type	Liwa et al. (2017)
Enzyme interactions	Inhibition or activation of enzymes affecting metabolic pathways.	Enzyme inhibitors (e.g. ACE inhibitors)	Varies by enzyme type and bioactive compound (e.g. protease inhibitors)	Kraithong et al. (2022)
Signal transduction	Influence on cellular signaling pathways that regulate functions.	Kinase pathway modulators, ion channel effects	Different pathways (e.g. MAPK, PI3K) influenced by specific compounds	Chen and Liu (2018)
Gene expression modulation	Alteration of gene expression impacting cellular functions.	Epigenetic modulators (e.g. HDAC inhibitors)	Specific genes and transcription factors affected vary by compound	Kumari et al. (2022)
Hormonal activity	Modulation of hormone activity affecting endocrine functions.	Insulin sensitizers, thyroid hormone modulators	Targets specific hormonal receptors and pathways (e.g. insulin receptors)	Chandra (2022)
Antioxidant actions	Neutralization of free radicals to reduce oxidative damage.	Vitamin C, glutathione	Varies by free radical type and antioxidant mechanism (e.g. scavenging vs. reducing)	Lv et al. (2021)
Anti-inflammatory mechanisms	Reduction of inflammation through various pathways.	NF-κB inhibitors, cytokine suppressors	Targets inflammatory pathways and cytokines (e.g. IL-6, TNF-α)	Ramírez-Moreno et al. (2022)
Immune system modulation	Enhancement or suppression of immune responses to improve health.	Immunostimulants, immunosuppressants	Specific immune cells or pathways (e.g. T-cell activation vs. suppression)	Vieira et al. (2024)
Cell cycle regulation	Modulation of cell division processes, often in cancer therapy.	Cyclin-dependent kinase inhibitors	Specific cell cycle checkpoints (e.g. G1/S transition)	Sun et al. (2022)
Apoptosis induction	Induction of programmed cell death in damaged or diseased cells.	Caspase activators, pro-apoptotic agents	Targets specific apoptosis pathways (e.g. intrinsic vs. extrinsic)	Forbes-Hernández et al. (2014)
Microbiome interaction	Interaction with gut microbiota influencing digestion and health.	Prebiotics, probiotics	Specific microbiota strains or metabolites influenced	Singh et al. (2019)
Bioavailability and metabolism	Absorption and metabolism of bioactive compounds in the body.	Lipophilic compounds, encapsulated forms	Variations in absorption and metabolism (e.g. fatty acids vs. water-soluble compounds)	Shahidi, Ramakrishnan, and Oh (2019)
Synergistic effects	The combined effects of compounds enhance overall benefits.	Combined antioxidants (e.g.,\ vitamins C and E)	Specific interactions and enhanced effects based on combined compounds	Putra et al. (2021)
Antagonistic effects	Diminishment of effects due to interactions between compounds.	Interaction between vitamins A and E	Specific compounds affecting each other's bioavailability or activity	Ren et al. (2020)
Clinical implications	Practical application of bioactive compounds in medical and therapeutic contexts.	Use in chronic disease management	Impact on specific diseases and treatment protocols	Serrano et al. (2015)

influencing a broad spectrum of cellular functions and responses. By interacting with various signaling molecules and receptors, these compounds can initiate or inhibit signal cascades that control processes such as cell growth, apoptosis, inflammation, and immune responses. For example, resveratrol, found in red wine, activates the sirtuin pathway, which is involved in the regulation of aging and longevity. Similarly, curcumin interferes with NF-kB signaling, a key pathway in inflammatory responses, thus exhibiting potential anti-inflammatory effects. This modulation of signaling pathways by bioactive compounds highlights their capacity to impact cellular health and disease outcomes significantly impact cellular health and disease outcomes, making them a focal point in the research for developing new therapeutic strategies (Azad and Wright 2012).

Bioactive compounds can significantly affect gene expression, leading to notable changes in protein synthesis and cell behavior. By interacting directly with the genetic material or through signal transduction pathways that affect transcription factors, these compounds can upregulate or downregulate the expression of specific genes. For example, compounds like sulforaphane found in cruciferous vegetables can activate genes involved in antioxidant responses, enhancing the body's ability to combat oxidative stress. Conversely, certain flavonoids can suppress oncogenes, reducing the risk of cancer development. This modulation of signaling pathways by bioactive compounds highlights their capacity to influence cellular health and disease outcomes, making them a focal point in research for developing new therapeutic strategies (Jaime and Santoyo 2021).

Bioactive compounds may influence the endocrine system by interacting with hormone receptors or synthesis pathways, potentially affecting hormonal balance. While some effects, such as the role of phytoestrogens in menopausal symptoms, are well-documented, others require further exploration to establish their clinical significance. For instance, phytoestrogens found in soy products can bind to estrogen receptors, potentially reducing the risk of breast cancer and alleviating menopausal symptoms by providing mild estrogenic effects (Suen, Kenan, and Williams 2022). Additionally, compounds like resveratrol have been shown to influence insulin secretion and sensitivity, playing a role in managing diabetes and metabolic disorders. This modulation of hormonal activity underscores the potential of bioactive compounds to treat and manage conditions that are influenced by hormonal imbalances (Mao et al. 2019).

Antioxidant actions and anti-inflammatory mechanisms are two critical areas where bioactive compounds play a significant role. Antioxidants such as vitamin C, vitamin E, and beta-carotene scavenge free radicals, preventing oxidative damage to cells and tissues which can lead to chronic diseases like cancer and heart disease. These compounds achieve this by donating electrons to free radicals without destabilizing themselves, thus breaking the chain of oxidative stress. On the other hand, anti-inflammatory bioactives like curcumin and omega-3 fatty acids help reduce the production of pro-inflammatory cytokines and inhibit the activation of pathways such as NF-kB, which are known to contribute to the inflammatory process. By controlling inflammation, these compounds can mitigate the severity of diseases characterized by chronic inflammation, such as arthritis, asthma, and inflammatory bowel disease (Balsano and Alisi 2009).

The influence of bioactive compounds extends to immune system modulation, cell cycle regulation, and apoptosis induction, playing crucial roles in promoting health and combating diseases. For instance, polysaccharides from mushrooms and echinacea can stimulate immune system activity by enhancing the production of immune cells and cytokines, providing better defense mechanisms against infections. Conversely, certain compounds can suppress excessive immune responses, which is beneficial in treating autoimmune diseases. Regarding cell cycle regulation, bioactives like sulforaphane can halt the proliferation of cancerous cells by interfering with various cell cycle phases. In contrast, others may induce apoptosis in damaged or abnormal cells, ensuring they do not proliferate uncontrollably. These multifaceted actions highlight the potential of bioactive compounds in preventive health strategies and therapeutic applications, signaling a dynamic area of ongoing and future research (Rein et al. 2013). Moreover, understanding these mechanisms is essential for designing effective fortification strategies in dairy products, ensuring that bioactive compounds remain stable, bioavailable, and efficacious during processing and storage.

Health benefits and physiological effects

Bioactive compounds are renowned for their extensive range of health benefits and physiological effects that contribute significantly to the prevention of chronic diseases and the promotion of overall health. Their antioxidant properties play a pivotal role in protecting cells from oxidative stress, a key factor in developing cardiovascular diseases, cancer, and neurodegenerative disorders. By neutralizing free radicals and reducing oxidative damage to DNA, proteins, and lipids, bioactive compounds help maintain cellular integrity and function (Campos 2018). Furthermore, the anti-inflammatory effects of bioactive compounds are crucial for mitigating the chronic inflammation associated with a wide array of health issues, including arthritis, diabetes, and inflammatory bowel disease. By inhibiting pro-inflammatory cytokines and enzymes, these compounds can reduce inflammation and its harmful effects on the body (Banwo et al. 2021).

Bioactive compounds have shown potential in promoting apoptosis in cancer cells and inhibiting tumor growth. However, much of this evidence is based on preclinical studies and requires further investigation in human trials. Their ability to modulate various signaling pathways involved in cell proliferation and death contributes to their potential as complementary agents in cancer prevention and treatment. Additionally, these compounds have been shown to improve metabolic health by enhancing insulin sensitivity, regulating blood lipid levels, and reducing the risk of metabolic syndrome and type 2 diabetes. Overall, emerging evidence suggests that bioactive compounds may influence the composition and function of the gut microbiota, potentially improving digestion and immune function. However, further research is needed to confirm these effects and their clinical relevance (Jaime and Santoyo 2021).

Neuroprotective effects are another significant benefit, with certain bioactive compounds that is, polyphenols being capable of protecting against neurodegenerative diseases such as Alzheimer's and Parkinson's by preventing neuronal damage, reducing amyloid-beta accumulation, and supporting cognitive function. However, while evidence supports the neuroprotective potential of bioactive compounds, further research is needed to establish definitive conclusions and therapeutic applications. Generally speaking, the health benefits and physiological effects of bioactive compounds are vast and varied, underscoring their importance in a balanced diet for maintaining health and preventing disease. Their incorporation into fortified dairy products offers a practical approach to delivering these benefits to a broad population, particularly targeting vulnerable groups such as children, the elderly, and those with specific dietary needs. Their potential for therapeutic applications continues to be a promising area of research, highlighting the need for further exploration into the mechanisms behind their benefits and their efficacy in disease prevention and management (Table 4) (Kurek et al. 2022). Moreover, emerging technologies like nanoencapsulation and liposomal systems enhance the stability and bioavailability of sensitive bioactives, ensuring their effectiveness in fortified foods. This technological advancement plays a critical role in maximizing the health benefits of bioactive compounds when incorporated into functional foods, such as dairy products.

Bioavailability and metabolism

Bioavailability and metabolism are critical factors that determine the efficacy of bioactive compounds in exerting their health benefits. Bioavailability refers to the proportion of a

Table 4. Bioactive compounds and their health benefits.

Bioactive compound	Health benefits	References
Vitamin D	Enhances calcium absorption, bone health, and immune function	Itkonen, Erkkola, and Lamberg-Allardt (2018)
Calcium	Crucial for bone health and muscle function	Cormick et al. (2021)
Omega-3 fatty acids	Supports cardiovascular health, cognitive function, and anti-inflammatory responses	Feizollahi, Hadian, and Honarvar (2018)
Probiotics	Promotes gut health, supports the immune system, and may reduce the risk of certain infections	Kaur Sidhu et al. (2020)
Vitamin A	Important for vision, immune function, and skin health	Wirth et al. (2017)
Iron	Essential for oxygen transport and energy production, prevents anemia	Kaur, Agarwal, and Sabharwal (2022)
Folic acid	Important for cell growth, DNA synthesis, and pregnancy health	Thurston, Borman, and Bower (2023)
Zinc	Supports immune function, wound healing, and DNA synthesis	Tsang et al. (2021)
Antioxidants (e.g. Vitamin E)	Protects cells from oxidative stress, supports heart health, and may reduce cancer risk	Ungurianu et al. (2021)

compound that enters the circulation when introduced into the body and can thus have an active effect. The metabolism of bioactive compounds involves their digestion, absorption, distribution, metabolism, and excretion, collectively known as ADME processes, which significantly influence their biological activity and effectiveness (Câmara et al. 2020).

The bioavailability of bioactive compounds is influenced by various factors, including their chemical structure, the matrix of the food in which they are contained, and interactions with other dietary components during processing and digestive passage. For instance, the solubility of a compound can affect its absorption in the digestive tract, with fat-soluble compounds often requiring dietary fats for optimal absorption. The presence of fibers and other compounds can either inhibit or facilitate the release and absorption of bioactive compounds (Rein et al. 2013). Advanced delivery systems, including encapsulation techniques, enhance the bioavailability of sensitive bioactives like omega-3 fatty acids and vitamins by protecting them during processing and digestion (Homroy et al. 2024).

Once absorbed, bioactive compounds undergo metabolism primarily in the liver, where they can be modified into more active, less active, or inactive forms. Metabolic transformations often involve conjugation reactions that increase the solubility of compounds, facilitating their excretion from the body. However, these transformations can also affect the compounds' bioactivity, either enhancing or diminishing their health benefits (Shahidi, Ramakrishnan, and Oh 2019). The extent to which bioactive compounds are metabolized and the pathways involved can vary significantly among individuals, influenced by genetic factors, age, sex, and gut microbiota composition. The gut microbiota, in particular, plays a crucial role in the metabolism of certain bioactive compounds, transforming them into metabolites that can have distinct biological activities from their parent compounds (Neilson, Goodrich, and Ferruzzi 2017). Moreover, dairy processing methods such as pasteurization and homogenization can impact the bioavailability and efficacy of added bioactive compounds. Studies indicate that encapsulation techniques, such as spray drying, liposomes, and emulsification, help protect heat-sensitive vitamins and antioxidants during processing, ensuring their stability and bioavailability in fortified dairy products (Gruskiene, Bockuviene, and Sereikaite 2021; Lavelli, D'Incecco, and Pellegrino 2021; Verma et al. 2021)

Understanding the bioavailability and metabolism of bioactive compounds is essential for assessing their potential health benefits and for designing functional foods and nutraceuticals that effectively deliver these compounds in bioavailable forms. It also highlights the importance of considering individual differences in metabolism when evaluating the efficacy of dietary interventions and supplements containing bioactive compounds (Ferreira, Martins, and Barros 2017). Furthermore, careful consideration of processing conditions and formulation strategies is necessary to optimize the delivery of bioactive compounds in fortified dairy products, ensuring consistent health benefits across diverse populations (Santillán-Urquiza et al. 2017).

Fortification of dairy foods with bioactive compounds

The fortification of dairy foods represents a pivotal advancement in nutritional science, aimed at enhancing the nutritional profile of dairy products to address public health concerns. This process involves the deliberate addition of bioactive compounds, such as vitamins, minerals, and other nutrients, to dairy products such as milk, yogurt, and cheese (Kaur, Agarwal, and Sabharwal 2022). The primary goal is to combat nutritional deficiencies in the general population and to offer products that support overall health and wellness. Technologies such as encapsulation have further enhanced the effectiveness of fortification by improving the stability and bioavailability of sensitive bioactives, ensuring their efficacy during processing and digestion. Fortification strategies are meticulously designed to ensure that the added nutrients remain stable and bioavailable, making dairy products an ideal vehicle or matrix for delivering essential nutrients to a wide audience (Ottaway 2008).

The fortification process involves a series of carefully designed steps to enrich dairy products with bioactive compounds. These steps include selecting nutrients based on public health needs, sourcing high-quality compounds, incorporating them using methods like direct addition or encapsulation, and conducting rigorous quality control to ensure safety, efficacy, and consumer acceptability. This process, supported by scientific evidence, enhances the nutritional value of dairy products while addressing challenges such as nutrient stability and sensory quality (Lawrence and Lawrence 2013).

The careful selection of nutrients based on public health needs and nutritional science is one of the initial steps in dairy fortification. Epidemiological data inform this selection on nutritional deficiencies and the known health benefits of specific bioactive compounds. For example, Swiss dairy giant Nestle has released an iron-fortified dairy drink for the Pakistan population, addressing the iron deficiency in the young population. Following nutrient selection, the sourcing of these compounds plays a vital role. Whether derived from natural sources or synthesized in laboratories, the purity and stability of bioactive compounds are paramount to the success of fortification efforts (Olson et al. 2021).

The fortification methods vary depending on the dairy product and the added nutrient/bioactive. Techniques such as direct addition, encapsulation, or co-precipitation effectively integrate nutrients into dairy foods. These methods are chosen based on their ability to preserve the nutrient's bioavailability and stability, ensuring that the final product delivers the intended health benefits. Once these nutrients are identified, they are sourced from natural ingredients or manufactured through synthetic processes to ensure purity and efficacy (Kruger et al. 2020). The chosen nutrients are then incorporated into dairy products through various techniques, including direct addition, encapsulation, or co-precipitation, depending on the nature of the nutrient and the product. This integration must be done carefully to maintain the stability of the nutrient and ensure it remains bioavailable, meaning the body can easily absorb it after consumption. Encapsulation at both nano and micro scales can protect heat-sensitive compounds during food processing. The final steps in the dairy fortification process involve stringent quality control measures to verify the concentration and stability of the added nutrients, as well as ensuring that the final product meets all safety standards (Fletcher, Bell, and Lambert 2004).

Consumer acceptance and sensory quality are critical components of the fortification strategy. Sensory mitigation strategies, such as encapsulation, help maintain the taste, texture, and appearance of fortified dairy products, ensuring they meet consumer expectations. Studies assessing consumer preferences and sensory characteristics provide valuable insights for industry professionals, facilitating the development of products that are both nutritious and appealing (Chen et al. 2023). Efforts to inform the public about the benefits of fortified dairy products and to ensure their availability and affordability contribute significantly to the success of fortification programs. These initiatives aim to foster a positive perception of fortified dairy foods and to encourage their integration into daily diets (Dwyer et al. 2015).

The impact of fortifying dairy products is initially highlighted in Table 5, which illustrates the substantial differences in nutrient content between fortified and non-fortified dairy items, showcasing the tangible benefits of fortification. This table provides a clear comparison of how essential nutrients are increased through the fortification process. Table 6 details the specific bioactive compounds found in dairy and their health benefits, linking the types of compounds to their functional effects.

Table 5. Fortified versus non-fortified dairy products.

Nutrient	Non-fortified milk (per serving)	Fortified milk (per serving)	Increase (%)
Calcium	300 mg	450 mg	50%
Vitamin D	100 IU	400 IU	300%
Vitamin A	500 IU	750 IU	50%
Iron	0.1 mg	4 mg	3900%
Vitamin B12	1.2 µg	2.4 µg	100%
Folic acid	0 µg	100 µg	N/A
Omega-3 fatty acids	0 mg	250 mg	N/A

Table 6. Bioactive compounds in dairy: types and health benefits.

Bioactive compound	Type found in dairy	Health benefits
Conjugated linoleic acid (CLA)	Naturally occurring and added	May reduce body fat and improve immune function
Probiotics	Added in fermented dairy products like yogurt	Enhance gut health and immune response
Bioactive peptides	Derived during fermentation	May lower blood pressure and have anti-inflammatory effects

Table 7. Health outcomes associated with consumption of fortified dairy products.

Health outcome	Fortified nutrient	Evidence of benefit
Bone health	Calcium, vitamin D	Improved bone density and reduced risk of fractures
Vision	Vitamin A	Supports good vision and reduces the risk of night blindness
Anemia prevention	Iron	Helps in the production of hemoglobin and reduces anemia risks
Nervous system health	Vitamin B12, folic acid	Supports nerve function and can prevent certain types of anemia
Heart health	Omega-3 fatty acids	May reduce cardiovascular disease risk factors

Table 7 further explores the health outcomes associated with consuming these fortified products, emphasizing the clinical implications and preventive health potentials of fortified dairy, such as improved bone health, cardiovascular health, and immune system support. By addressing common nutritional deficiencies and contributing to a more nutrient-dense diet. Fortified dairy foods can significantly improve public health by providing health benefits, particularly for vulnerable populations such as children, pregnant women, and the elderly, who are at greater risk of nutritional deficiencies. Targeted fortification strategies can address specific health needs, such as calcium and vitamin D fortification for bone health in children and the elderly, or iron fortification for reducing anemia in women of reproductive age (Cardoso et al. 2019). The enhanced nutritional value and added health benefits of fortified dairy products thus underscore the potential of fortification to significantly improve the quality of dairy products, thereby contributing to better health outcomes and addressing public health concerns related to nutrient deficiencies (Bagchi 2014).

Incorporation methods of bioactives in dairy foods

The incorporation of bioactive compounds into dairy products involves a variety of methods, each chosen based on the

Table 8. Comparison of bioactive compounds and their incorporation methods in dairy products.

Bioactive compound	Source	Incorporation method	Resulting health benefit	References
Vitamins	Plant extracts, synthetic sources	Direct addition	Nutritional enhancement, immune support	Nzekoue et al. (2021)
Beta-glucans	Fungi, oats	Direct addition	Cholesterol management, immune modulation	Antontceva et al. (2019)
Dietary fibers	Grains, fruits	Direct addition	Digestive health, nutrient absorption	Arora, Patel, and Chauhan (2015)
Minerals	Natural sources, synthetic	Direct addition	Bone health, metabolic regulation	Ocak and Rajendram (2013)
Omega-3 fatty acids	Fish oil, algae	Encapsulation	Cardiovascular health, anti-inflammatory effects	Ghorbanzade et al. (2017)
Polyphenols	Fruits, vegetables	Encapsulation	Antioxidant properties reduced oxidative stress	Zam (2016)
Carotenoids	Carrots, tomatoes	Encapsulation	Eye health, antioxidant benefits	Conboy Stephenson, Ross, and Stanton (2021)
Peptides	Dairy proteins	Fermentation	Antihypertensive effects, muscle recovery	Ayati et al. (2022)
Probiotics	Bacterial cultures	Fermentation	Gut health, improved digestion	Khalili et al. (2020)

specific properties and health benefits of the bioactives. These methods include direct addition, encapsulation, and fermentation, each with distinct advantages and applications (Table 8).

Direct addition

This straightforward method involves incorporating bioactives like vitamins or plant extracts directly into dairy formulations. It allows for the fortification of products such as milk with essential nutrients like vitamin D or the addition of plant extracts rich in antioxidants, such as berry or green tea extracts. While effective, direct addition can present challenges related to stability, sensory attributes, and interactions with other ingredients. In this context, "quality" refers to the combination of sensory attributes (taste, texture, appearance), nutritional value (bioavailability and efficacy of added bioactives), and safety standards (compliance with regulatory requirements) that meet consumer expectations and ensure product acceptability. Therefore, careful consideration is necessary to maintain the desired product quality (Kruger et al. 2020).

Encapsulation methods

Techniques such as various types of nano and microencapsulationsystems offer advanced solutions for protecting and controlling the release of bioactive compounds within dairy products. These methods are beneficial for stabilizing sensitive bioactives, ensuring their efficacy during processing, storage, and digestion.

Nanoencapsulation involves encapsulating bioactive compounds in nanoscale carriers, enhancing their stability and bioavailability. Nanoemulsions are especially effective for dispersing lipophilic bioactives, such as omega-3 fatty acids, into aqueous matrices, making them ideal for incorporation into milk and yogurt (Akhavan-Mahdavi et al. 2024). Studies have shown that nanoencapsulated forms of vitamins and minerals, such as vitamin D and iron, exhibit higher oxidation resistance and improved sensory characteristics, addressing challenges like the metallic taste or off-flavors (Akhavan-Mahdavi et al. 2024).

Liposomes provide a protective lipid bilayer around bioactive compounds, shielding them from degradation during processing and improving their absorption in the gastrointestinal tract. Recent research demonstrates that liposomal delivery systems effectively preserve heat-sensitive bioactives like curcumin and omega-3 fatty acids, ensuring their therapeutic potential remains intact (Ghorbanzade et al. 2017; Mirzazadeh et al. 2024).

Microencapsulation involves enclosing bioactive compounds in a protective matrix to shield them from environmental factors and ensure sustained release. Microencapsulation has been successfully applied to fortify yogurt with vitamin E and cheese with beta-glucans, maintaining their antioxidant activity and shelf life. Additionally, microencapsulation can protect probiotics during processing, enhancing their survival rate and effectiveness in fermented dairy products.

These advanced technologies not only improve the stability and bioavailability of bioactive compounds but also mitigate sensory changes, such as unpleasant tastes or odors, which are common challenges in dairy fortification. For instance, nanoencapsulated fish oil maintains its anti-inflammatory properties while reducing its characteristic fishy flavor, making it more acceptable to consumers (Ghorbanzade et al. 2017; Katouzian et al. 2017). Furthermore, encapsulation techniques like spray drying and emulsification help protect heat-sensitive bioactives, such as curcumin and polyphenols, ensuring their functionality throughout the product lifecycle (Kaptan 2025).

Fermentation

This method leverages probiotic strains to naturally enhance the bioactivity of dairy products. During fermentation, probiotics such as Lactobacillus and Bifidobacterium produce beneficial bioactive peptides that contribute to improved gut health, immune function, and antioxidant activity. Fermented dairy products, such as yogurt and kefir, benefit from these added bioactives, offering additional health advantages beyond traditional nutrition. This method not only enhances the product's health benefits but also improves nutrient availability and reduces lactose content, making it a valuable approach for developing functional dairy products (Homayouni Rad et al. 2016; Nagpal, Kumar, and Kumar 2012). Fermentation also plays a critical role in addressing public health concerns by targeting specific population groups, such as children and the elderly, who may require enhanced nutrient intake. By selecting appropriate probiotic strains and optimizing fermentation conditions, dairy producers can tailor the health benefits of their products to meet the unique needs of these groups (Drago and Valencia 2002). Impact of Fortified Dairy Foods Containing Bioactive Compounds on Public Health

Influence on overall nutrition

The influence of fortified dairy products on overall nutrition extends beyond merely addressing nutritional deficiencies; it actively contributes to the optimization of dietary patterns and the promotion of health and wellness. Fortified dairy products, such as milk enriched with omega-3 fatty acids, play a crucial role in enhancing cardiovascular health, while yogurts fortified with probiotics may improve gut health and immune function (Adinepour et al. 2022). Additionally, the inclusion of plant sterols and stanols in dairy products like cheese has been shown to effectively reduce blood cholesterol levels, exemplifying the potential of these fortified foods to contribute to chronic disease prevention. In this regard, encapsulation systems have further enhanced the stability and bioavailability of these bioactive compounds, ensuring their efficacy during processing and digestion. Table 9 provides a comprehensive overview of the nutritional deficiencies prevalent in specific populations or regions and how fortified dairy products address these with added nutrients, alongside the recommended daily amounts and their subsequent impact on health.

Fortified dairy foods improve nutrition by incorporating stable and bioavailable bioactive compounds that interact beneficially within the dairy matrix (Adinepour et al. 2022). Techniques used in the fortification process ensure that these bioactive compounds remain potent and effective after processing, storage, and consumption. Furthermore, consumer acceptance and preference for these fortified products are crucial for their successful integration into daily diets, underscoring the importance of focusing on sensory properties and effective product marketing. The strategic fortification of dairy foods holds promise for making significant contributions to overall nutrition, addressing public health concerns related to nutrient deficiencies, and aiding in preventing nutrition-related chronic diseases. Continued research and innovation in the development of fortified dairy products are essential to maximize their health benefits and ensure their effective role in enhancing the nutritional quality of diets worldwide. Targeted fortification strategies can address specific health needs, such as calcium and vitamin D fortification for bone health in children and the elderly, or iron fortification for reducing anemia in women of reproductive age. These strategies highlight the importance of interdisciplinary research to tailor fortification practices to meet the unique nutritional requirements of vulnerable populations (Buttriss and Lanham-New 2020).

Public health implications for specific demographic groups

Fortified dairy products have the potential to significantly address the unique nutritional needs of specific demographic groups, including children, pregnant women, the elderly, and individuals with specific dietary restrictions. By tailoring fortification strategies to meet the requirements of these populations, fortified dairy foods can play a pivotal role in improving public health outcomes (Rohner et al. 2023). Childhood is a critical period for growth and development, making adequate nutrition essential; fortified dairy products, particularly those enriched with calcium and vitamin D, are vital for promoting bone health and preventing conditions such as rickets (Dewi and Mahmudiono 2021). Additionally, iron-fortified milk can help combat iron deficiency anemia, which is prevalent among young children in many regions (Basrowi and Dilantika 2021). Similarly, pregnant women require an increased intake of certain nutrients, such as folic acid and iron, to support fetal development and maternal health. Mandatory fortification programs, such as the addition of folic acid to milk, have been shown to reduce the incidence of neural tube defects in newborns (Dewi and Mahmudiono 2021), while iron fortification in milk can also address anemia during pregnancy, ensuring optimal health for both mother and child. Moreover, aging is associated with an increased risk of osteoporosis and other age-related conditions due to declining nutrient absorption and changing dietary habits. Fortified dairy products, especially those enriched with calcium and vitamin D, can mitigate these risks by supporting bone density and reducing the likelihood of fractures (Patel, Desai, et al. 2022; Patel, Pushpadass, et al. 2022).

Table 9. Nutrient fortification: deficiencies, doses, and impacts.

Nutritional deficiency	Prevalent in population/region	Nutrient added	Recommended daily amount	Impact on health
Vitamin D deficiency	Northern climates with limited sunlight exposure	Vitamin D	600–800 IU	Improved bone health by enhancing calcium absorption, reduced risk of bone fractures, and improved immune function.
Calcium deficiency	Adolescents, postmenopausal women, and the elderly	Calcium	1000–1300 mg	Prevention of osteoporosis and maintenance of healthy bone structure, reduced risk of osteopenia and bone fractures.
Iron deficiency anemia	Women of reproductive age, children, and vegetarians	Iron	8–18 mg	Improved oxygen transport and energy levels, reduction in the risk of anemia, and enhanced cognitive function.
Iodine deficiency	Populations in regions with low soil iodine levels	Iodine	150 µg	Prevention of goiter, improved thyroid function, and crucial for fetal brain development during pregnancy.
Vitamin A deficiency	Low-income countries with limited access to diverse diets	Vitamin A	700–900 µg RAE	Enhanced immune function, reduced risk of night blindness, and support for healthy skin and eye health.
Omega-3 fatty acids deficiency	Populations with low fish consumption	Omega-3 Fatty Acids	250–500 mg	Reduced risk of cardiovascular diseases, support for mental health and cognitive function, and anti-inflammatory effects.
B12 deficiency	Vegetarians, vegans, and the elderly	Vitamin B12	2.4 µg	Prevention of megaloblastic anemia, support for nerve function, and essential for DNA synthesis.
Folate (folic acid) deficiency	Women of childbearing age	Folic Acid	400 µg	Reduced risk of neural tube defects in newborns, support for DNA synthesis and cell division.

Omega-3 fatty acids and antioxidants in fortified dairy can further contribute to cognitive health and reduce inflammation, benefiting older adults. In addition, for individuals following vegetarian diets that include dairy, fortified products offer a valuable source of these nutrients to support overall health. fortified dairy alternatives provide essential nutrients like vitamin B12, which are often lacking in plant-based diets (Rohner et al. 2023). Similarly, low-fat or lactose-free fortified dairy products cater to those with specific health concerns, ensuring they receive necessary nutrients without compromising their dietary preferences. By targeting these specific populations, fortified dairy products can address pressing public health issues and promote better health outcomes. Policymakers and health practitioners must consider these tailored approaches when designing fortification programs to maximize their impact on vulnerable groups (Suchdev et al. 2020).

Role in preventing chronic diseases

The burgeoning interest in the nexus between diet and health has spotlighted bioactive compounds as pivotal agents in the prevention and mitigation of chronic diseases. These naturally occurring compounds, found in a wide array of foods, possess potent biological activity that influences various metabolic pathways and biological systems. The chronic diseases in question, including cardiovascular disease, diabetes, cancer, and neurodegenerative disorders, constitute a significant portion of the global disease burden, underscoring the critical importance of preventive strategies. This discourse aims to elucidate the mechanisms through which bioactive compounds exert their beneficial effects, drawing on current scientific evidence to underscore their potential in chronic disease prevention (Noce, Romani, and Bernini 2021).

Dairy products fortified with polyphenols demonstrate antioxidant capabilities by scavenging free radicals and reducing oxidative stress, which may help mitigate chronic inflammation—a known contributor to various chronic diseases. While promising, the extent of their impact on disease prevention remains under investigation. Beyond their antioxidant properties, bioactive compounds in fortified dairy such as carotenoids and dietary fibers contribute to a range of health benefits from enhancing vision to promoting gut health and reducing cancer risks. Omega-3 fatty acids, included in some dairy products, have been associated with cardiovascular health due to their anti-inflammatory and lipid-lowering effects. However, individual responses may vary, and long-term clinical studies are necessary to fully understand their efficacy. Table 10 summarizes the effects of these fortified dairy products on the main chronic diseases, highlighting how they mitigate major risk factors and promote health.

Bioactive compounds also play a crucial role in modulating signal transduction pathways within cells, thereby influencing a broad spectrum of cellular functions and responses. According to Ungurianu, Zanfirescu, and Margină (2023) resveratrol, often found in fortified dairy products, activates the sirtuin pathway, which is involved in regulating aging and longevity (Ungurianu, Zanfirescu, and Margină 2023). Similarly, curcumin interferes with NF-κB signaling, a key pathway in inflammatory responses, thus exhibiting potential anti-inflammatory effects (Kahkhaie et al. 2019). In addition to addressing general populations, fortified dairy products offer targeted solutions for specific demographic groups, such as children, pregnant women, and the elderly, who may be at greater risk of chronic diseases due to nutritional deficiencies or age-related vulnerabilities. Vitamin D-fortified milk supports bone health in children and reduces the risk of osteoporosis in the elderly, while folic acid fortification helps prevent neural tube defects in newborns (Kruger et al. 2018).

Despite their promise, it is essential to approach claims about the therapeutic potential of bioactive compounds with caution, as many remain under investigation. While some bioactives, such as probiotics and omega-3 fatty acids, have well-established roles in chronic disease prevention, others, like certain plant extracts, require further research to validate their efficacy (Martinez-Armenta et al. 2021). Careful consideration of study limitations, such as small sample sizes and reliance on preclinical models, is necessary to

Table 10. The potential therapeutic benefits of bioactive compounds across a range of chronic conditions.

Disease/condition	Effects of bioactive compounds	References
Blood pressure lowering	Bioactive peptides inhibit ACE, leading to reduced angiotensin II levels, vasodilation, and lowered blood pressure.	Malinowski et al. (2020)
Anticancer	Certain compounds exhibit anticarcinogenic actions through antioxidative, anti-inflammatory, and cell cycle-modulating mechanisms.	Asma et al. (2022)
Antidiabetic	Compounds such as phenolics and flavonoids modulate glucose metabolism and insulin sensitivity, reducing diabetes risk.	Tran, Pham, and Le (2020)
Anti-Alzheimer	Bioactive compounds counteract amyloid-beta plaque formation and tau protein aggregation, offering neuroprotection.	Panda and Jhanji (2020)
Neuroprotective effects	These compounds support neuronal health by preventing oxidative stress and inflammation and promoting brain function.	Socała et al. (2020)
Bone health	Polyphenols and other bioactives promote bone density and health by influencing mineralization and bone metabolism.	Valentino et al. (2021)
Obesity and related issues	Bioactive substances can aid in managing body weight, improving insulin resistance, lowering blood pressure, reducing chronic inflammation, modulating lipid profiles, and mitigating oxidative stress.	Konstantinidi and Koutelidakis (2019)

ensure an accurate representation of their health benefits. Moreover, the incorporation of bioactive compounds into dairy products must account for challenges such as sensory changes, stability during processing, and interactions with other nutrients. Encapsulation techniques help protect heat-sensitive bioactives like vitamins and omega-3 fatty acids, ensuring their effectiveness after consumption. Such advancements enhance the practical application of fortified dairy products in public health interventions (Mohite and Waghmare 2020).

Current research on fortified dairy products

Dairy products are among the most consumed foods in various countries and present a viable option for delivering bioactives (Adinepour et al. 2022). Liquid milk fortification with specific micronutrients, particularly vitamin D and iron, is mandatory in several countries, including Canada, Costa Rica, Honduras, Finland, and China. In Latin America, countries like Costa Rica and Honduras have implemented mandatory fortification of liquid milk with vitamins A and D to address nutritional deficiencies, particularly among children (Allen 2006). Additionally, voluntary fortification with nutrients such as calcium and vitamin D is encouraged in many regions to support bone health and prevent deficiencies in vulnerable populations. The dairy industry of several countries fortifies dairy products with micronutrients, of which vitamin D and Vitamin A are the most common. Vitamin D fortification, in particular, has been instrumental in preventing rickets in children, while vitamin A fortification addresses deficiencies prevalent in low-income regions (Zahedirad et al. 2019). Vitamin D, vitamin A, vitamin C, vitamin E, niacin, thiamin, riboflavin, vitamin B12, pyridoxine, iron, zinc, calcium, folic acid, and magnesium are common micronutrients which are used by the industry for fortification.

Incorporating dairy products fortified with bioactive compounds into daily diets poses a significant challenge in food fortification, yet it can produce foods with improved consumer acceptance and new biological characteristics (Adinepour et al. 2022). The challenge lies not only in achieving an effective concentration of bioactives but also in ensuring their stability, bioavailability, and sensory quality during processing and storage. The major challenge lies in achieving an effective concentration of bioactives that can positively impact health, while also considering the potential negative effects on the sensory properties of the final product, such as taste, appearance, and odor (Rashidinejad, Birch, and Everett 2016).

Adverse environmental factors such as oxygen levels, light exposure, and temperature fluctuations, as well as the rigorous conditions of food processing like high temperatures and pressure, along with the conditions of the upper digestive tract, may lead to the impairment or decrease in the functionality and activity of bioactive compounds (Mohammadian et al. 2020). Milk compounds, especially proteins, tend to interact with bioactives and form complexes. These complexes are formed through a combination of hydrophilic and hydrophobic interactions, resulting in either hydrophobic or hydrophilic complexes. The non-covalent associations, which are the main type of interaction, are facilitated by van der Waals and hydrophobic bonds. On the other hand, in irreversible associations, covalent bonds are established between bioactives and milk proteins, leading to permanent changes in the protein structure. Under specific conditions such as pH, protein perpetual deposition can occur due to reversible associations. Additionally, the interactions between proteins and bioactives used in dairy products can also impact the antioxidant function (Rashidinejad et al. 2015; Rashidinejad et al. 2022).

Bioactive components incorporated into dairy products have shown that iron can bind with milk proteins, particularly casein, resulting in the formation of a complex that hinders iron absorption in the gastrointestinal system, consequently reducing iron bioavailability. Furthermore, the interaction between iron and casein in the presence of oxygen speeds up the oxidation process of lipids in milk, leading to an undesirable taste and smell in the product (Adinepour et al. 2022).

Dairy products can be fortified with nutrients such as vitamins and minerals to enhance their nutritional value and health benefits (de Romaña, Olivares, and Pizarro 2018). Several researchers have confirmed the interaction between milk protein and vitamin E among various vitamins. Through hydrophobic bonds, vitamin E forms a complex with milk proteins, leading to a reduction in its bioavailability and antioxidant activity. Additionally, this interaction results in negative alterations in the final product (Tan et al. 2018). During an investigation into the enhancement of a yogurt product with vitamin E, it was discovered by the researchers that the gel-like characteristics of yogurt were compromised. This was due to the fact that the bonding of vitamin E with yogurt proteins disrupted the equilibrium of compounds, resulting in a decrease in water absorption by proteins and ultimately causing a reduction in water-holding capacity and an increase in syneresis (Tan et al. 2018).

Fortification of milk with vitamin D has been successful in preventing rickets in children (Wagner et al. 2008). Some countries in Latin America have implemented milk fortification programs specifically targeted toward children, resulting in a decrease in the prevalence of anemia (Iglesias Vázquez et al. 2019). In addition to vitamins, dairy products can also be fortified with dairy minerals to enhance their fresh dairy flavor notes (Goff 2013). Fiber enrichment is another area where dairy products can be fortified, with various fibers such as inulin, gum Arabic, polydextrose, and soluble soybean polysaccharides successfully incorporated into dairy products. Controlling protein-polysaccharide phase separation is important in these fortified products (Goff 2013). Kandyliari et al. (2023) fortified dairy products (e.g. kefir, cream cheese, and yogurt) and plant-based vegan yogurt with aqueous extracts of plant byproducts and herbs, examining their phenolic profiles, antioxidant content, and organoleptic characteristics. Their findings indicated that fortification with plant and herbal extracts enhanced the health benefits of both dairy and plant-based products. Sharifan et al. (2022) studied the influence of nano-encapsulated vitamin D in fortifying low-fat milk and yogurt on bone health metrics. These researchers reported that there were no significant differences in bone mineral density and trabecular bone scores of intervention and control groups. However, the study highlights the importance of optimizing encapsulation methods to ensure consistent bioavailability and efficacy of vitamin D in fortified dairy products. Hashim et al. (2021) fortified nonfat yogurt with whey protein isolate (WPI) and found that the nonfat yogurt containing 3 and 7% WPI exhibited similar sensory and textural qualities as the full-fat yogurt. WPI proves to be an effective substitute for fat in creating low-fat yogurt with specific attributes. Melilli et al. (2021) fortified fiordilatte cheese with inulin from *Cichorium intybus* or *Cynara cardunculus*. The sensory analysis revealed that the inclusion of inulin in fiordilatte resulted in enhanced preservation of sensory quality during storage. Notably, the overall quality of the fortified cheese was consistently higher ($p < 0.05$) compared to the control sample. In another study (Pandule et al. 2021), the impact of incorporating flaxseed oil (2.9%–5.1%) and flaxseed–whey protein concentrate (WPC) emulsion (4.8%–8.6%) into cream as a source of omega-3 fatty acids was assessed. The study focused on analyzing the thermal, sensory, and physico-chemical characteristics of the resulting butter. Fortified butter revealed lower saturated fat content compared to the control sample. The developed butter showed improved spreadability. Encapsulation technologies play a critical role in protecting omega-3 fatty acids from oxidation and preserving their health benefits during processing and storage.

Lastly, it should be said that encapsulation technologies are advanced technologies with great potential for the protection of bioactive compounds throughout various stages such as processing, storage, and even specific segments of the digestive system. Table 11 illustrates the incorporation of bioactive compounds into milk, yogurt, and milk-based drinks.

The technology of dairy product fortification is straightforward and does not require specialized machinery. Although the fortification of dry and liquid milk products differs, for both, bioactive compounds such as soluble vitamins and minerals can be added directly. In contrast, fat-soluble vitamins in the oily form are typically homogenized with a portion of milk before mixing with the bulk milk. The fortification processes for dry milk and liquid milk are depicted schematically in Figure 1 (Mannar and Hurrell 2018).

Stability and bioavailability of bioactive compounds from fortified dairy products

The incorporation of carotenoids and dietary bioactive lipids like phytosterols into dairy products has recently become a topic of great interest. Carotenoids, including β-carotene which is a precursor of vitamin A, can positively impact heart and vision functions while reducing the risk of various cancers. Moreover, the antioxidant properties of these natural pigments have led researchers to consider fortifying dairy products like yogurt and ice cream with these compounds to minimize the use of synthetic pigments. Nevertheless, challenges such as low bioavailability, high melting point, and susceptibility to environmental factors like light and heat are associated with using carotenoids such as carrot waste and red pepper waste in dairy products (Rostamabadi, Falsafi, and Jafari 2019).

The majority of bioactives that have been researched for their inclusion in milk and dairy products belong to the phenolic group. These substances frequently possess a unique taste (bitter and astringent), distinct color, and physicochemical properties that impact the flavor of dairy products due to potential interactions with proteins. The degradation of these bioactives under different environmental conditions, their insolubility, and the uneven dispersion of various polyphenols like curcumin, whole grape, garlic, and chokeberry extract pose additional obstacles when incorporating them into milk and dairy products (Adinepour et al. 2022).

While there is an increasing focus on enriching various foods with minerals, calcium, and iron are the primary ones receiving significant emphasis. Even though milk and milk-derived products are naturally abundant in calcium, their bioavailability varies depending on factors such as fortification methods, processing techniques, and dietary interactions (Palacios, Hofmeyr, et al. 2021). The bioavailability of calcium in cow's milk is generally estimated at 30–35%, which is considered higher than many plant-based sources but lower than fortified alternatives (McCourt and O'Sullivan 2022). However, when milk is fortified with specific forms of calcium, such as calcium citrate or calcium gluconate, the bioavailability can increase significantly, reaching up to 40% in some cases. In addition, processing techniques play a critical role in determining calcium bioavailability (Figure 2).

Pasteurization and homogenization, common practices in milk production, do not significantly affect the natural bioavailability of calcium in milk (Zhang et al. 2024). Nevertheless, the addition of certain bioactive compounds, such as phytates or oxalates, during fortification or through dietary interactions may reduce calcium absorption by forming insoluble complexes. On the other hand, the inclusion of vitamin D in fortified dairy products enhances calcium absorption by promoting its uptake in the intestines, thereby improving overall bioavailability. Moreover, a comparative analysis of calcium bioavailability across different dairy products reveals notable differences (Mattar et al. 2022). In cheese, the bioavailability of calcium is often higher than in liquid milk due to its lower phosphate content and slower digestion rate, which allows more time for calcium absorption Fortified yogurt has been shown to enhance calcium bioavailability compared to non-fortified varieties, particularly when fortified with bioavailable forms like calcium carbonate or calcium lactate. While plant-based milk substitutes are often fortified with calcium, their bioavailability is typically lower than that of cow's milk due to the presence of inhibitors like phytates. To address this issue, encapsulation techniques, such as nanoencapsulation, have been explored to improve calcium stability and bioavailability in these alternatives (Palacios, Cormick et al. 2021).

Long-chain unsaturated fatty acids, known as essential fatty acids, are a crucial component of our diet. Dairy products, in particular, are ideal candidates for fortification with

Table 11. Examples of dairy products fortified with encapsulated bioactive compounds.

Bioactive compound	Product	Encapsulation Technique	The effects of encapsulation	References
Vitamin D3	Milk	Nanoencapsulation via freeze-drying	Increasing the solubility of vitamin D3 Low release in similar gastric conditions and high release after 8 h in solution with similar intestinal pH	Hasanvand et al. (2015)
Vitamin E	Yogurt beverage	Emulsification	Maintain the amount of vitamin E within 28 days Greater antioxidant activity Acceptable number of lactic acid bacteria after thermal processing (>106 cfu/g)	Raikos et al. (2021)
Vitamin E, A and CoQ10	Cheese	Emulsification	Compatibility between bioactives during co-encapsulation High chemical stability during storage Protecting vitamins during the cheese-making process	Stratulat et al. (2014)
Vitamin C	Ice cream	Liposomal encapsulation	Higher over run (85%) No ice crystals in ice cream Sensory acceptance Higher resistance to melting (11% < the control sample after 2h) - Preserve vitamin C	Tsyrendorzhieva et al. (2021)
Iron	Low-fat milk	Liposomal and emulsification	Effective in preventing lipid oxidation Excluding metallic taste Slight differences in sensory properties ($p > 0.05$)	Abbasi and Azari (2011)
Fish oil	Fermented probiotic milk	Emulsification	Reduction of oxidation of EPA and DHA ($p < 0.05$) Increased survival of Lactobacillus plantarum Low peroxide value (0.57 mEq/kg) No effect on sensorial properties	Moghadam et al. (2019)
Fish oil	Yogurt	Emulsification	Preservation of polyunsaturated fatty acid content against oxidation (90.40%) Acceptable sensory feature	Hamed et al. (2019)
Fish oil	Siahmezgi cheese	Emulsification	Low oxidation Sensory acceptance	Zakipour Rahimabadi (2021)
Oil of wheat germ	Labneh cheese	Casein micelles	High radical inhibition Oxidative stability Improved hardness (12.5 N), springiness (0.99 mm), and chewiness (6.6 N × mm)	Nour Soliman et al. (2019)
Oil of olive and extract of dill	Cheese	Emulsification	A higher number of Lactobacillus (7.8 log CFU.g-1) in the oil-encapsulated sample - Higher unsaturated fatty acid content - Higher antioxidant activity in encapsulated extract samples	Ivanova et al. (2020)
Oil of basil	Ice cream	Spray drying	Higher antioxidant content (94.57%) More phenolic compounds (76.80 µg GAE/mL) Improvement overrun and viscosity	Paul et al. (2020)
Curcumin	Milk	Nanoencapsulation via spray drying	High thermal stability High radical inhibition (61.43%) Ineffective on sensory characteristics	Patel, Desai, et al. (2022)
Curcumin	Manchego cheese	Emulsification	High antioxidant activity Increased phenolic content Taste similar to the control sample	Sardiñas-Valdés et al. (2021)
Extracts of pepper	Labneh cheese	Extrusion	Preservation of phenolic content Significant increase in antioxidant content ($p < 0/05$) Prevent the growth of mold and yeast High sensory score	Balabanova et al. (2020)
Extract of fig leaves	Cheese Sauce	Freeze drying	Absence of mold and yeast in samples with encapsulated extract after 50 days - Acceptance of sensory features	Elsayed et al. (2021)
β-carotene of extract carrot waste	Yogurt	Extrusion	Provide part of the β-carotene required by the daily diet - Preservation of physical and chemical properties of enriched product during 28 days of storage at 4 °C - Higher antioxidant activity after 28 days	Šeregelj et al. (2021)

these compounds due to their widespread consumption and popularity. However, incorporating essential fatty acids like fish oil, flaxseed oil, and echium oil directly into dairy products poses certain challenges. These challenges include the unpleasant odor and taste associated with these fatty acids, as well as their low bioavailability and susceptibility to oxidation (Razi and Rashidinejad 2021; Yesiltas et al. 2019).

The stability of bioactive compounds, specifically their capacity to withstand variations in pH, ionic strength, and temperature, is a crucial factor to consider when developing bioactive compounds -enriched dairy products. A range of studies have explored the stability and bioavailability of bioactive compounds in fortified dairy products. The stability of bioactive compounds in fortified dairy products varies depending on the specific compound and the fortification method. Encapsulation protects bioactives against processing stresses and improves their release in the digestive tract (McClements 2018). The various means used to create encapsulated particles include spray drying and spray chilling, fluidized bed drying, hot melt, coacervation, encapsulation, extrusion, rotating disks, hydrogel, and nanoparticles (Drusch and Berg 2008; Krasaekoopt, Bhandari, and Deeth 2004). The bioactive food molecules that are already encapsulated in industrial applications utilize lipids, proteins, and

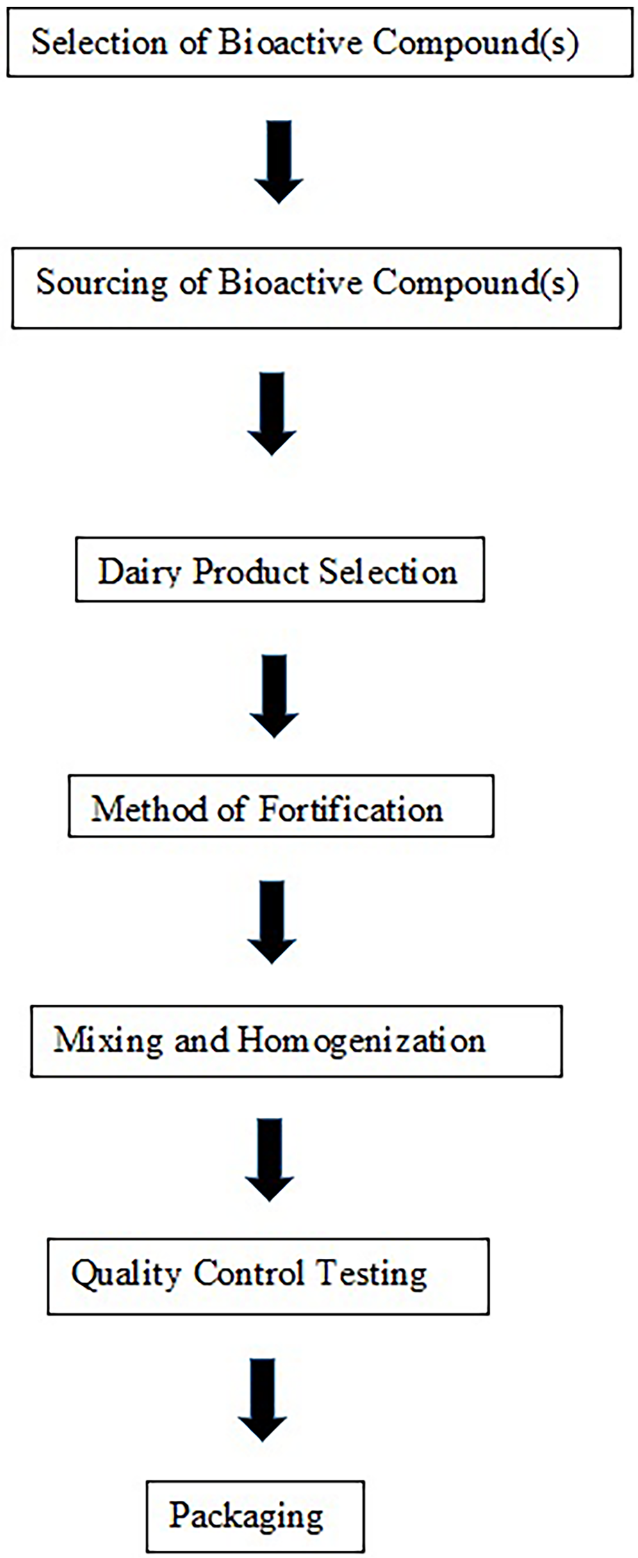

Figure 1. Flowchart of the dairy fortification process.

carbohydrates as their encapsulating material (Augustin and Hemar 2009). These ingredients are usually encapsulated to resist the high acidity and enzyme activity of the stomach and duodenum but also because of their low water-solubility that interferes with application in many food products.

Further, the addition of bioactive in food formulation also compliments the existing nutritional and functional properties of the food system. Kandyliari et al. (2023) found that plant extracts in fortified dairy products can enhance antioxidant content and phenolic profile, with a bioavailability range of 4%–68%. El-Hak et al. (2016) reported that fortification with date sirup, pomegranate sirup, and sesame paste can increase the bioavailability of minerals and antioxidants in dairy products. Ranjan et al. (2005) discovered that fortification with calcium gluconate can improve the bioavailability of calcium in buffalo milk. Paswan et al. (2021) highlighted the potential of herbs and spices to fortify dairy products with bioactive compounds, enhancing their functional and medicinal attributes.

Public perception and acceptance of fortified dairy foods

The evolution of fortified dairy products has marked a significant development in nutritional science, aiming to combat nutrient deficiencies and improve overall health. As these products become increasingly available, understanding public perception and acceptance is crucial for their successful integration into daily diets. Consumer awareness of the health benefits associated with fortified dairy foods plays a pivotal role in this acceptance. Fortified foods, enriched with essential vitamins and minerals like vitamin D, calcium, and omega-3 fatty acids, promise enhanced nutritional value beyond that of their natural counterparts (Palacios, Hofmeyr, et al. 2021). However, the acceptance of fortified dairy products is not solely predicated on awareness of their health benefits. Taste and product quality are paramount considerations for consumers, often outweighing the perceived nutritional advantages. The sensory attributes of dairy products, including flavor, texture, and appearance, must meet or exceed consumer expectations for these products to find a place in the market (Shegelman et al. 2019). This indicates that while fortification adds value, it should not compromise the intrinsic sensory qualities that consumers have come to expect from dairy products. Several key factors influence consumer choices and preferences regarding fortified dairy products which are shown in Table 12.

Price sensitivity further complicates the landscape of consumer acceptance. Often, fortified dairy products are priced higher than non-fortified alternatives due to the added cost of fortification and marketing. This price differential can be a significant barrier to widespread adoption, particularly among price-conscious consumers or those in lower income brackets. Thus, making these products affordable and accessible is a key challenge that needs addressing to enhance consumer acceptance (Sadat-Ali et al. 2013). To address affordability concerns, subsidies, discounts, and targeted pricing strategies could be implemented, especially for populations at higher risk of nutrient deficiencies, such as children, pregnant women, and the elderly. Clear, transparent labeling and effective communication about the health benefits of fortified dairy products are essential for influencing consumer decisions. Consumers today are more informed and health-conscious than ever, seeking out products that contribute positively to their well-being. Well-designed labels that communicate the specific benefits of fortified dairy, such as

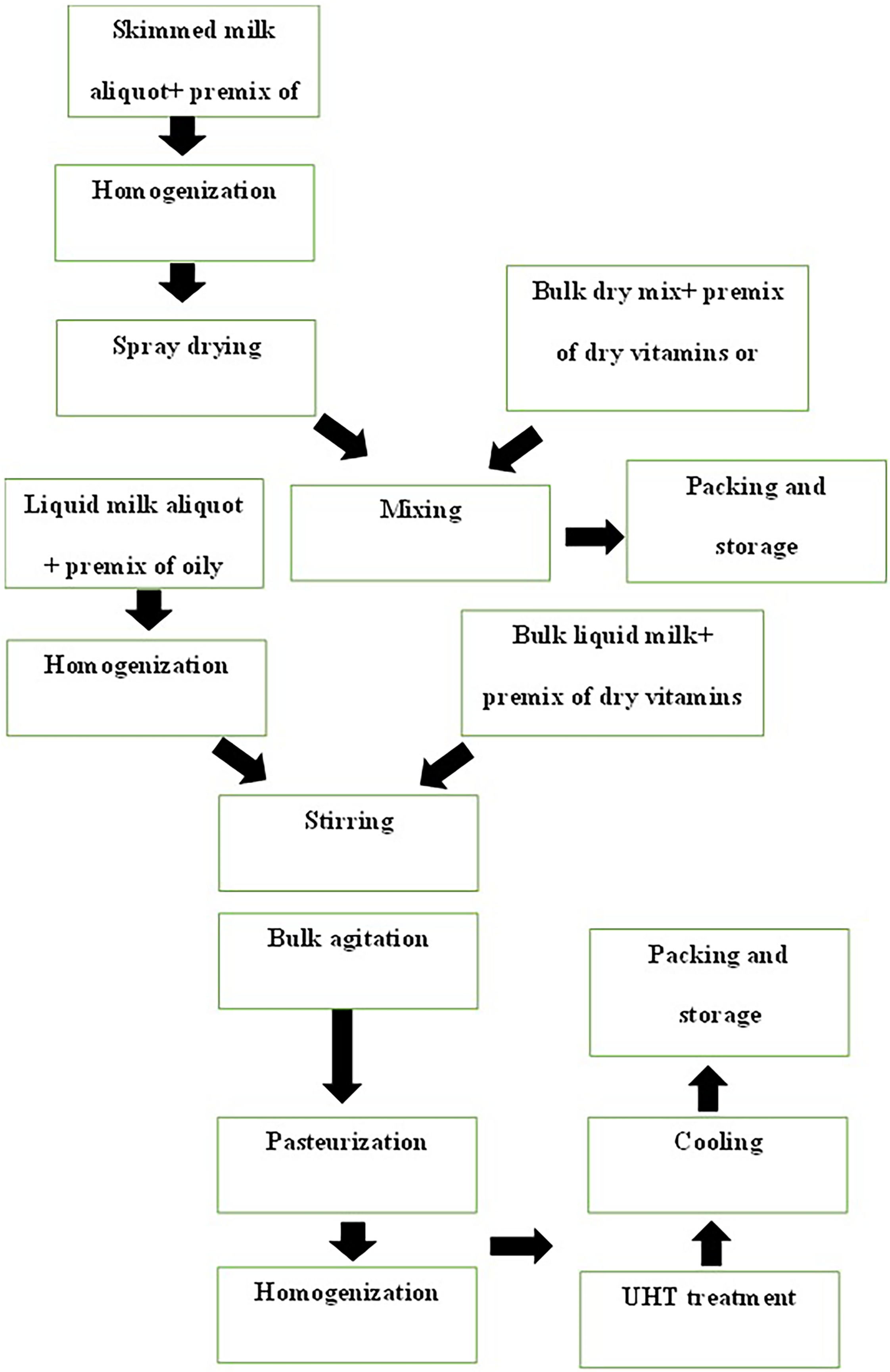

Figure 2. Fortification of dry milk (a) and liquid milk (b) with bioactive compounds. Adapted from Mannar and Hurrell (2018).

Table 12. Factors influencing consumer choices and preferences of functional dairy foods.

Factors	Description
Health benefits	Consumers are more likely to choose fortified products for their health and wellness benefits, such as improved bone health and enhanced immune function.
Taste and product quality	The sensory attributes of fortified dairy products, including taste, texture, and appearance, play a crucial role in consumer selection despite the health benefits.
Price sensitivity	The higher cost of fortified products compared to non-fortified ones can deter some consumers, making affordability a significant factor in their choices.
Labeling and information	Effective and transparent labeling that communicates the health benefits of fortified products is a key influencer of consumer decisions.
Cultural and social influences	Cultural preferences and social norms influence the acceptance and consumption of fortified dairy products among different consumer groups.

bone health or immune support, can guide consumers in making informed choices about their dietary intake. Moreover, labels should clearly distinguish between well-established health benefits and emerging evidence, ensuring claims are presented with appropriate caution to align with scientific rigor (El-Salam, El-Shibiny, and Mehanna 2017).

Cultural and social influences also play a substantial role in the acceptance and consumption of fortified dairy foods. Dietary habits and preferences are deeply rooted in cultural traditions and practices, which can either facilitate or hinder the adoption of fortified products. Understanding these cultural contexts is critical for tailoring marketing strategies and product formulations to meet the preferences of diverse consumer groups (El-Salam, El-Shibiny, and Mehanna 2017).

Strategies to promote the acceptance of fortified dairy foods must be multi-faceted, addressing the complex interplay of health awareness, taste preferences, affordability, and cultural considerations. Educational campaigns aimed at raising awareness about the importance of specific nutrients and how fortified dairy can contribute to meeting dietary needs are foundational. Such initiatives can help shift perceptions and highlight the added value of fortified products in a balanced diet (Khalili et al. 2020). These campaigns should emphasize the role of fortified dairy in addressing specific population needs, such as calcium and vitamin D for bone health in children and the elderly, or iron fortification for reducing anemia in women of reproductive age (Khalili et al. 2020).

Improvements in product formulation are also essential to ensure that fortified dairy foods are indistinguishable from their traditional counterparts in terms of taste and quality. Research and development efforts focused on maintaining or enhancing sensory attributes while adding nutritional value can help overcome consumer skepticism related to taste and product quality.

Addressing affordability involves not only setting competitive prices but also educating consumers about the long-term health benefits and potential cost savings associated with improved nutrition. Subsidies, discounts, and other financial incentives can also be explored to make fortified dairy products more accessible to a broader segment of the population (Liberato and Pinheiro-Sant'Ana 2006). Transparent and informative labeling, coupled with effective marketing strategies, can demystify fortified dairy products for consumers. By providing clear information on nutrient content and health benefits, along with appealing packaging, companies can enhance product visibility and appeal. Social media and other digital platforms offer valuable channels for engaging with consumers directly, offering education, and gathering feedback to refine product offerings (Abou-Zeid 2016).

Lastly, collaboration with healthcare professionals, nutritionists, and dietitians can lend credibility to the health claims of fortified dairy products. Endorsements from trusted health experts can reassure consumers about the safety and benefits of these products, encouraging their inclusion in daily diets. As the global population becomes increasingly proactive about health and nutrition, fortified dairy foods stand at the forefront of dietary innovation, offering a promising avenue for enhancing nutritional intake and improving public health outcomes (Arora, Shree, and Gupta 2011). The acceptance and consumption of fortified dairy products are influenced by a complex interplay of factors related to consumer awareness, health benefits, sensory qualities, affordability, and cultural norms. Addressing these factors through targeted strategies can significantly enhance public perception and acceptance of fortified dairy foods, thereby contributing to improved nutritional outcomes in the population (Picciotti et al. 2022).

Safety considerations and regulatory framework for dairy fortification

In dairy fortification, a thorough understanding and assessment of the safety of bioactive compounds are paramount. The risk assessment of these compounds is a multifaceted approach involving several methodologies to ensure their safety when introduced into dairy products. This includes comprehensive toxicological studies that evaluate the potential toxicity of bioactive compounds over various concentrations and durations of exposure (Granato et al. 2010). Allergenicity assessments are also critical, particularly for new compounds or those derived from sources that may contain allergens. These assessments help in identifying any possible allergic reactions that could affect consumer health. Additionally, dosage evaluations are conducted to determine the safe levels of each compound, ensuring that they remain within the limits that are both effective and non-harmful (Playne, Bennett, and Smithers 2003). Furthermore, emerging technologies like nanoencapsulation have been developed to minimize risks associated with variability in bioactive stability and bioavailability during processing and storage (Granato et al. 2010).

The interaction of bioactive compounds with the existing nutrients in dairy products also requires careful consideration. Bioactive compounds can interact with vitamins, minerals, and other intrinsic components of dairy, which can either enhance or inhibit the absorption and efficacy of these nutrients. For example, certain bioactive compounds might chelate with minerals such as calcium or iron, potentially reducing their bioavailability (Corbo et al. 2014). On the other hand, synergistic interactions might occur, enhancing the nutritional value of the dairy product. Understanding these interactions is crucial not only for ensuring the safety of the fortified dairy product but also for maintaining its nutritional integrity. These interactions are studied through nutrient-nutrient interaction assessments, which help formulate fortification strategies that avoid negative effects and ensure that the consumer receives the intended health benefits (Homayouni et al. 2012). Thus, the risk assessment and evaluation of interactions with existing nutrients form the backbone of the safety considerations in the fortification of dairy foods with bioactive compounds. This comprehensive approach ensures that fortified dairy products are safe for consumption and that their introduction into the market is responsibly managed to avoid any adverse health impacts (O'Brien 2003).

The regulatory landscape for the fortification of dairy products is governed by a set of comprehensive international guidelines and standards that aim to ensure product safety, efficacy, and quality. Globally recognized standards such as those set by the Codex Alimentarius provide a universal framework that harmonizes fortification practices across countries, helping to facilitate international trade while safeguarding consumer health. In the United States, the Food and Drug Administration (FDA) oversees the fortification of dairy products to prevent nutrient deficiencies and ensure that any additions are safe and appropriately labeled. Similarly, the European Union (EU) has specific regulations that not only dictate the types of nutrients that can be added to dairy products but also set stringent limits on their quantities to prevent overconsumption (Anastasova et al. 2018).

Each region may have unique requirements or allowances that reflect local public health needs and nutritional policies. For example, in some countries, fortification of dairy with vitamin D is mandatory due to the high prevalence of vitamin D deficiency and low sunlight exposure, while in others, such fortification may be voluntary or focused on different nutrients like folic acid or iodine. These regional differences necessitate that dairy producers and distributors are well-versed in and compliant with the specific regulations applicable to their markets (Kanekanian 2014).

Compliance and monitoring are critical components of the regulatory framework. This involves several processes designed to ensure that fortified dairy products meet the stipulated guidelines. Labeling requirements are a fundamental aspect, requiring clear and accurate labels that inform consumers about the nutrient content and any added bioactive compounds. Nutrient content verification is another crucial process, where the actual nutrient levels in the dairy products are periodically tested to ensure they align with what is declared on the label. Safety evaluations are conducted regularly to check for any potential adverse effects arising from the fortified nutrients (Siró et al. 2008).

Government agencies are primarily responsible for overseeing these compliance activities, but third-party organizations also play a significant role in certifying that products meet specific safety and quality standards. These organizations might conduct independent testing and provide certification that can help build consumer trust and confidence in fortified dairy products. Together, these regulatory standards and compliance mechanisms ensure that fortified dairy products are not only beneficial in addressing nutritional deficiencies but also safe for consumer use, thereby supporting public health objectives effectively (Granato et al. 2020).

Ensuring consumer safety in the context of fortified dairy products extends beyond regulatory compliance to encompass transparency, labeling, and educational initiatives. Transparency in labeling is paramount, as it serves to inform consumers about the presence of bioactive compounds and their intended health benefits in the products they are purchasing. Clear and accurate labeling, which includes detailed information on the type and amount of each bioactive compound, helps consumers understand what they are consuming and the potential health impacts. This level of transparency is crucial not only for consumer safety but also for building trust. When consumers feel informed about what is in their food, their confidence in making health-conscious decisions increases, which in turn can lead to greater acceptance and consumption of fortified products (Toma and Pokrotnieks 2006).

Educational initiatives play a critical role in complementing labeling efforts. These initiatives are designed to inform the public about both the benefits and potential risks associated with consuming fortified dairy products. By providing balanced information through various channels such as public health campaigns, informational brochures at points of sale, or digital content, consumers can gain a more comprehensive understanding of how these products fit into a healthy diet. Education can highlight the role of fortified dairy in preventing nutrient deficiencies, the importance of dosage, and the concept of a balanced diet, thereby empowering consumers to make informed dietary choices (Žuntar et al. 2020). Furthermore, these educational efforts should aim to reach diverse audiences, including those at higher risk of nutritional deficiencies, healthcare professionals, educators, and caretakers. Effective communication strategies that consider cultural sensitivities and literacy levels are essential to ensure that the message is not only delivered but also understood by all segments of the population. Engaging with community leaders and healthcare providers to endorse and disseminate this information can amplify the reach and impact of these initiatives, ultimately enhancing public health outcomes through informed consumer choices (Smith and Charter 2011).

The fortification of dairy products with bioactive compounds faces significant challenges, primarily due to the variability in the sources of these compounds and the rapid pace of scientific discovery. The quality and concentration of bioactive compounds can vary greatly depending on their source, whether natural or synthetic. Natural variations in plant or animal-derived compounds can be influenced by factors such as soil quality, climate, and farming practices, which in turn can affect the consistency and safety of the final fortified dairy product. Ensuring uniformity in the bioactive content of these products requires rigorous quality control processes and standardization protocols, which can be complex and costly to implement (Thakur, Sharma, and Singh 2023). Moreover, the safety and efficacy of fortified dairy products are contingent upon the stability of these bioactive compounds during processing, storage, and even upon consumption. Variability in these compounds can lead to inconsistent health benefits or unintended side effects, complicating regulatory approvals and consumer acceptance. Manufacturers must continuously monitor and adjust their fortification processes to compensate for these natural variances, ensuring that each batch of product meets the required safety and nutritional standards. In addition to these variability challenges, regulatory frameworks must continually adapt to emerging science. As new research uncovers more about the health impacts of various bioactive compounds, regulations governing their use in food products must evolve to reflect these findings. This includes updating permissible use levels, reevaluating safety data, and possibly reclassifying certain compounds based on new health information. Regulatory bodies need to maintain a dynamic approach to fortification policies to ensure they adequately protect public health without stifling innovation (Bagchi 2014).

This need for adaptability in regulation presents its own set of challenges, including ensuring that regulatory changes are based on solid scientific evidence and implemented in a way that allows industry compliance without undue burden. Collaboration between scientists, industry stakeholders, and regulators is crucial to effectively navigate the complexities of fortifying dairy products with bioactive compounds (Thakur, Sharma, and Singh 2023). This collaboration ensures that as new beneficial compounds are discovered, they can be safely and effectively incorporated into public diets, enhancing health outcomes without compromising product safety. As the fortification of dairy products with bioactive compounds becomes more prevalent, it is imperative to address the safety considerations and regulatory standards that ensure these practices are both safe and effective. Section 7 delves into these crucial aspects, outlining the risk assessments, regulatory compliance measures, and consumer safety initiatives that accompany the fortification process. This discussion ensures a comprehensive understanding of the safeguards in place to protect public health while enhancing the nutritional value of dairy products (O'Brien 2003).

Future implications and challenges

The integration of bioactive compounds into dairy products through fortification presents a promising avenue for enhancing public health nutrition. However, the journey from conceptualization to widespread acceptance and implementation is fraught with various challenges and implications for the future. This section explores the potential developments, challenges, and barriers in the fortification of dairy foods with bioactive compounds, emphasizing the need for multidisciplinary approaches to navigate these complexities effectively (Ghorbanzade et al. 2017).

Maintaining organoleptic properties of fortified food products is one of the primary future implications that involves the ongoing research and development required to optimize the fortification process. As our understanding of bioactive compounds deepens, there is a continuous need to innovate in how these nutrients are incorporated into dairy products without compromising taste, texture, or stability (Gerhart and Schottenheimer 2018). Advances in food technology and nanotechnology offer potential solutions, such as microencapsulation techniques that can improve the bioavailability and sensory attributes of fortified products. However, these technological advancements also necessitate significant investment in research and development, posing a challenge for the dairy industry, especially for small-scale producers (Zahedirad et al. 2019).

Economic considerations, including the cost of fortification and its impact on product pricing, also pose significant challenges. Ensuring that fortified dairy products remain affordable and accessible to all segments of the population is essential for achieving public health objectives. This requires innovative solutions to minimize production costs and strategic partnerships to support the distribution of fortified products in underserved communities (El-Kholy et al. 2011; Szajnar et al. 2017).

Conclusions

The enrichment of dairy products with bioactive compounds signifies a notable progression in public health nutrition, providing a practical approach to tackle prevalent nutritional deficiencies and fight chronic diseases. This review emphasizes the manifold advantages of fortified dairy products, spotlighting their contribution to enhancing the nutritional value of dairy foods, aiding in disease prevention, and ultimately bettering public health outcomes. The evidence discussed in this paper illustrates the positive influence of bioactive compounds like vitamins, minerals, fatty acids, and probiotics when integrated into dairy products. These compounds have demonstrated potential in reducing risk factors associated with cardiovascular diseases, osteoporosis, and diabetes, among other health conditions. While certain benefits, such as vitamin D's role in bone health, are well-established, others, including cancer prevention, remain subjects of ongoing research and require further validation through large-scale clinical trials. Furthermore, the fortification process holds the potential to significantly reduce the incidence of micronutrient deficiencies, especially in susceptible populations. However, the path from research to implementation is fraught with challenges. Factors such as consumer acceptance, regulatory compliance, cost-effectiveness, and technological constraints must be carefully addressed. The successful incorporation of fortified dairy products into the diet necessitates collaborative efforts from various stakeholders, including researchers, food scientists, policymakers, and the dairy industry, along with continuous consumer education.

Innovation in formulation and delivery systems, including encapsulation, can support effective fortification strategies. Interdisciplinary research exploring the bioavailability, efficacy, and long-term health impacts of bioactive compounds in dairy products is essential. Such efforts will deepen our understanding of the potential of dairy fortification and inform best practices and policy development. Based on the evidence and discussions presented, fortifying dairy foods with bioactive compounds shows considerable promise as a public health intervention. However, it is important to approach claims related to complex diseases, such as cancer and neurodegenerative disorders, with caution, given the current reliance on preclinical or small-scale human studies. Leveraging the widespread consumption of dairy products to deliver essential nutrients offers a strategic opportunity to improve nutritional status and reduce the global burden of chronic diseases. Nonetheless, maintaining scientific rigor and avoiding overstatements about therapeutic potential, especially where evidence is still emerging, is critical. Ultimately, dairy fortification represents a key component in advancing public health nutrition and promoting a healthier global population.

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