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Review article

Vitamin D fortification of dairy products: strategies, technologies, and health impacts

Fortificación de lácteos con vitamina D: estrategias, tecnologías y efectos en la salud

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Abstract

Vitamin D deficiency is a widespread global health concern driven by limited dietary sources, reduced sun exposure, and lifestyle changes. This narrative review synthesizes current evidence on the rationale, technologies, efficacy, and public health implications of vitamin D fortification of dairy products. A literature search was conducted in PubMed, Web of Science, and Scopus for English-language studies, including original research, randomized controlled trials, systematic reviews, meta-analyses, and relevant regulatory or technical documents. The literature examined vitamin D metabolism, the structural properties of dairy matrices that may enhance vitamin D stability and absorption, technological strategies for fortification, global regulatory frameworks, and clinical studies evaluating fortified dairy products. The evidence suggests that the lipid and protein components of milk, yogurt, and cheese can help protect vitamin D from degradation and enhance its bioavailability. Technological advances, including microencapsulation, nanoemulsions, and protein-based delivery systems, may further improve stability during processing and storage. Countries with mandatory fortification policies appear to achieve higher population vitamin D intakes than those relying on voluntary practices. Randomized controlled trials generally show that fortified dairy products can increase serum 25-hydroxyvitamin D concentrations in children, adults, and older populations, although the magnitude of the response varies across studies. Overall, dairy-based vitamin D fortification appears to be a useful strategy to improve vitamin D status, although broader and more coordinated approaches are still needed to address global deficiency.

Keywords: Vitamin D fortification. Dairy products. Bioavailability. Food technology.

Resumen

La deficiencia de vitamina D es un importante problema de salud mundial relacionado con fuentes alimentarias limitadas, reducción de la exposición al sol y los cambios en el estilo de vida. Esta revisión narrativa sintetiza la evidencia actual sobre la justificación, las tecnologías, la eficacia y la relevancia para la salud pública de la fortificación de los productos lácteos con vitamina D. La búsqueda bibliográfica se realizó en PubMed, Web of Science y Scopus, considerando estudios publicados en inglés, incluyendo artículos originales, ensayos clínicos aleatorizados, revisiones sistemáticas, metaanálisis y documentos regulatorios o técnicos relevantes. La bibliografía examinada incluyó el metabolismo de la vitamina D, las características estructurales de las matrices lácteas que pueden favorecer la estabilidad y la absorción de la vitamina D, las estrategias tecnológicas para la fortificación, los marcos normativos y los estudios clínicos que evaluaron productos lácteos fortificados. La evidencia sugiere que los lípidos y las proteínas de la leche, el yogur y el queso pueden proteger a la vitamina D de la degradación y favorecer su biodisponibilidad. Las innovaciones tecnológicas, como la microencapsulación, las nanoemulsiones y los sistemas de administración basados en proteínas, podrían mejorar aún más la estabilidad durante el procesamiento y el almacenamiento. Los países con políticas de enriquecimiento obligatorio parecen lograr una mayor ingesta poblacional de vitamina D que aquellos que dependen de prácticas voluntarias. Los ensayos clínicos muestran, en general, que los productos lácteos fortificados pueden aumentar las concentraciones séricas de 25-hidroxivitamina D en niños, adultos y personas mayores, aunque la magnitud de la respuesta varía entre estudios. En conjunto, la fortificación de los lácteos con vitamina D parece ser una estrategia útil para mejorar el estado de vitamina D, aunque se requieren enfoques más amplios y coordinados para abordar la deficiencia a nivel mundial.

Palabras clave: Fortificación con vitamina D. Productos lácteos. Biodisponibilidad. Tecnología de alimentos.

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Introduction

Vitamin D deficiency is widely recognized as a major global public health challenge. Despite the dual origin of vitamin D, cutaneous synthesis through UVB exposure and limited dietary intake, multiple lifestyles, environmental, and physiological factors have contributed to declining endogenous production worldwide, including urbanization, pollution, reduced outdoor activity, sunscreen use, and increasing adiposity, which sequesters vitamin D in adipose tissue[1,2]. Natural dietary sources remain scarce and are consumed in limited amounts, as foods such as fatty fish, egg yolk, or UV-exposed mushrooms are not staples in most populations[3].

Chile reflects this global trend in a particularly concerning way. Recent national evidence demonstrates alarmingly high rates of vitamin D deficiency. A study in schoolchildren found that 80.4% were vitamin D deficient during winter, with even lower levels in those with overweight or obesity[4]. Similar deficiencies have been documented across Europe, Latin America, and Asia[5,6], emphasizing the need for population-level interventions.

Food fortification has emerged as one of the most effective and sustainable public health strategies to improve vitamin D status. Among available food vehicles, dairy products are particularly suitable due to their physicochemical structure, lipid environment, and widespread consumption[7,8]. The dairy matrix, including casein micelles, whey proteins, and milk fat globules, enhances vitamin D stability and absorption, outperforming many non-dairy matrices[9].

Technological innovations have further strengthened this potential. Encapsulation techniques, nanoemulsions, and protein-based delivery systems enhance the stability of vitamin D during processing, storage, and digestion[10,11]. Several countries, including Canada, Sweden, and Finland, have already implemented mandatory fortification, achieving measurable improvements in population vitamin D status[12,13].

However, despite the growing body of evidence supporting vitamin D fortification, important gaps remain regarding the comparative advantages, technological feasibility, and practical implementation of dairy-based fortification strategies. Current literature is often fragmented, focusing separately on vitamin D metabolism, food technology, regulatory frameworks, or clinical outcomes, with limited integration of these perspectives into a comprehensive approach applicable to both the food industry and public health decision-making. This review synthesizes current evidence on vitamin D metabolism, the role of dairy matrices, technological strategies for fortification, regulatory aspects, and the efficacy of fortified dairy products in enhancing serum 25-hydroxyvitamin D (25(OH)D) levels. By integrating nutritional, technological, and regulatory perspectives, this review aims to provide useful evidence for researchers, the food industry, and policymakers involved in the design and implementation of fortification strategies aimed at reducing vitamin D deficiency worldwide.

Methodology

This review considered studies published between 1995 and 2025. A literature search was conducted using the PubMed, Web of Science (WoS), and Scopus databases. The following keywords and combinations were used: “vitamin D”, “dairy”, “delivery systems”, “dairy fortification”, “fortification technologies”, and “regulatory framework”. Only articles published in English were included. Original research articles, randomized controlled trials, systematic reviews, meta-analyses, and relevant regulatory or technical documents related to vitamin D fortification in dairy products were considered for inclusion.

Vitamin D: synthesis, absorption, metabolism, and dietary sources

Vitamin D is a secosteroid compound that can be synthesized endogenously or obtained through dietary intake. Cutaneous synthesis is initiated by exposure to ultraviolet B (UVB) radiation, which converts 7-dehydrocholesterol in the skin into previtamin D_3, subsequently transformed into vitamin D_3 (cholecalciferol). Owing to this endogenous synthetic capacity, vitamin D is considered a prohormone rather than a classical vitamin. Two major forms of vitamin D are recognized: vitamin D_2 (ergocalciferol), primarily derived from plant and fungal sources, and vitamin D_3 (cholecalciferol), predominantly obtained from animal sources and cutaneous synthesis. Endogenous synthesis represents the principal determinant of vitamin D status, contributing up to 80% of circulating vitamin D concentrations, whereas dietary intake generally accounts for the remaining proportion[1,2]. Following cutaneous production, vitamin D is transported in circulation bound mainly to vitamin D-binding protein (DBP). Dietary vitamin D is absorbed in the small intestine together with dietary lipids, incorporated into chylomicrons, and subsequently transported to the liver via the lymphatic system and systemic circulation.

Vitamin D undergoes two sequential hydroxylation reactions to achieve biological activation. The first hydroxylation occurs in the liver, generating 25(OH)D, the major circulating metabolite and the accepted biomarker of vitamin D status, reflecting both endogenous synthesis and dietary intake[14,15]. The second hydroxylation occurs primarily in the kidney, producing the biologically active form, 1,25-dihydroxyvitamin D (1,25(OH)2D).

Natural dietary sources of vitamin D are limited, and relatively few foods contain physiologically significant concentrations. Vitamin D_3 is mainly present in foods of animal origin, including fatty fish (e.g., salmon, tuna, and trout), fish liver oils, egg yolk, and fortified dairy products. Vitamin D_2 is primarily found in fungi, yeasts, and some algae. As a fat-soluble vitamin, vitamin D concentrations in foods are strongly influenced by lipid content, animal feeding practices, and exposure to UVB radiation. For example, wild salmon generally contains higher concentrations of vitamin D than farmed salmon due to differences in diet and environmental exposure[16]. In plant-derived foods, UVB exposure substantially increases vitamin D_2 concentrations,

particularly in mushrooms. Although vitamin D_2 has traditionally been associated with the plant kingdom, certain members of the Solanaceae family have also been shown to contain vitamin D_3 and its precursor, 7-dehydrocholesterol, in leaves and flowers[17].

In recent years, algae and microalgae have gained increasing scientific interest as potential vitamin D sources. These organisms constitute an important component of the aquatic food web and may contribute indirectly to the vitamin D content of fish species. Furthermore, microalgae exposed to higher seasonal UVB radiation exhibit increased vitamin D synthesis, with higher concentrations observed during summer compared with winter periods[18]. Given the high global prevalence of vitamin D insufficiency and deficiency, and considering that habitual dietary intake alone is often insufficient to rapidly restore adequate status, public health strategies such as food fortification and supplementation have emerged as effective and feasible approaches to improve vitamin D nutrition at the population level[19].

Dairy as a vehicle for vitamin D fortification

An emerging body of research highlights that the nutritional effects of dairy foods are influenced not only by their nutrient content but also by their complex structural matrix. Milk and fermented dairy products provide unique matrix structures that naturally encapsulate and protect vitamin D, thereby enhancing its stability and bioavailability[7].

In milk, added vitamin D_3 preferentially partitions into the lipid phase of the milk fat globules, an emulsion of microscopic triglyceride droplets surrounded by the milk fat globule membrane (MFGM), a complex phospholipid-protein coating. The MFGM stabilizes fat droplets and has been shown to shield vitamin D against degradation, for example, by limiting oxidative reactions and preventing acid-induced isomerization of the vitamin in the stomach[8]. Vitamin D diffuses into the fat globule's hydrophobic core, and the intact MFGM acts as a barrier that preserves the vitamin during common processing steps (e.g., pasteurization) and storage. Upon digestion, fragments of the MFGM facilitate emulsification with bile salts, promoting the incorporation of vitamin D into mixed micelles for intestinal absorption[9].

In addition to the lipid phase, dairy proteins contribute significantly to vitamin D's stability and dispersibility. Casein micelles, colloidal aggregates of casein proteins, are ~50-500 nm in size and have a porous, sponge-like structure that allows them to bind lipophilic micronutrients. Vitamin D can be non-covalently entrapped within casein micelles in the aqueous phase of milk, a particularly important mechanism in low-fat or skim milk, where fewer fat globules are present to carry the vitamin[20]. Indeed, casein micelles are being explored as natural nanocarriers for vitamin D fortification, allowing vitamin D_3 to be stably added to milk without adversely affecting the milk's sensory or functional properties[11]. Whey proteins, particularly β-lactoglobulin, play a crucial role in enhancing the bioaccessibility of vitamin D_3 in milk. Their hydrophobic binding sites facilitate the solubilization of vitamin D_3 within the aqueous phase, which is especially relevant in low-fat or skim milk, where fewer fat globules are available to carry the vitamin. During digestion, whey proteins and their peptide fragments contribute to the stabilization of mixed micelles, supporting the efficient incorporation of vitamin D_3 into the micellar phase and improving its intestinal availability[21].

Research comparing different dairy food vehicles shows that milk, yogurt, and cheese can all effectively deliver vitamin D, with each matrix offering particular advantages in terms of stability and bioavailability. In fortified fluid milk, vitamin D remains highly stable throughout processing and shelf life. Studies report minimal to no degradation of vitamin D_3 during pasteurization or even ultra-high-temperature (UHT) processing of milk, as the vitamin is encapsulated by milk fat and proteins[9]. Proper storage further ensures stability: for instance, light-induced oxidation of vitamin D in milk is negligible when packaged in light-opaque containers[22].

Fermented dairy products, such as yogurt, similarly show excellent vitamin D retention. Full-fat yogurt fortified with vitamin D_3 has been shown to retain approximately 87-91% of the added vitamin after fermentation and up to 28 days of refrigerated storage (4°C)[23]. Even in low-fat yogurt, a high percentage of vitamin D can be preserved over its shelf life, with 68-71% retention after 21 days of storage at 4°C[23]. Cheese also provides an effective protective matrix for vitamin D. During cheese-making, the fat-soluble vitamin D added to milk largely partitions into the curd with the milk fat, achieving high retention (often 90% or more) in the fresh cheese[9]. Although non-dairy systems lack the structural advantages of dairy products, they could effectively deliver vitamin D_3 by designing colloidal systems to prevent gastric degradation and enhance intestinal bioavailability. Randomized crossover trials have shown that the food matrix significantly influences vitamin D_3 bioavailability; for instance, simple plant matrices, such as apple juice, yield significantly lower bioavailability. To address the limitations, delivery systems such as nanostructured lipid carriers (NLCs) and nanoemulsions have emerged as highly effective alternatives. These nanocarriers can efficiently encapsulate vitamin D_3, decreasing its release in the acidic gastric environment (9.4% to 29.6% at pH 1.2) and ensuring its absorption in the intestinal phase[24].

Fortifying plant-based dairy alternatives poses structural challenges, as these beverages lack the complex network of casein micelles and MFGM naturally present in bovine milk. To counteract this structural characteristic, novel strategies are being developed to prevent droplet coalescence and degradation during digestion. For example, forming emulsion gels with soy protein isolate cross-linked with soluble dietary fibers, such as stachyose, creates a dense, uniform network that traps oil droplets and increases the micellar bioaccessibility of vitamin D_3 to nearly 70%[25].

Similarly, stabilizing oat milk with pea protein isolate and corn arabinoxylans effectively prevents droplet coalescence during the oral and gastric phases, thereby maintaining colloidal stability[26].

Low-energy complex nanoemulsions combining pea protein and Tween 80 offer another strategy, forming unique "clusters on a string" structures that enhance the transport efficiency of vitamin D across intestinal cells by 5.6-fold compared to the non-encapsulated vitamin[27].

Finally, the choice of the lipid carrier within plant-based matrices is critical; nanoemulsions utilizing oils rich in monounsaturated fatty acids (MUFAs), such as corn oil, are digested more rapidly and completely than those using polyunsaturated oils (PUFAs) like flaxseed or fish oil, leading to significantly higher vitamin D_3 bioaccessibility (up to 78%) by reducing the steric hindrance for lipase activity[28]. In summary, the existing literature highlights the importance of the food matrix, demonstrating that a well-designed food delivery system enables effective fortification of products with vitamin D.

Fortification technologies

Different strategies have been employed to fortify dairy products with vitamin D, including animal feed supplementation, direct irradiation, and the direct addition of vitamin D concentrates to milk. Among these, the direct fortification method is considered the most reliable, effective, and widely accepted by the dairy industry[29]. The main goal of fortification is to ensure the stability, bioavailability, and homogeneous distribution of vitamin D throughout processing, storage, and digestion.

Effective fortification technologies must preserve the sensory attributes of the product, guarantee nutrient retention, and comply with good manufacturing practices[9]. The efficiency of these technologies depends largely on the interaction between the dairy matrix (fat, casein, whey proteins, micronutrients), the chemical form of vitamin D (D_2, D_3, or 25-hydroxyvitamin D_3), and its physical form (free, encapsulated, or emulsified)[9]. Losses of vitamin D during processing and storage are mainly due to oxidation and isomerization, which have been reported across different fortified systems. Additional instability can result from vitamin D adsorption onto packaging materials or degradation in aqueous matrices, particularly in low-fat or skimmed products. Such alterations may affect both the appearance and flavor of fortified beverages, reducing consumer acceptability[10].

Beyond formulation aspects, processing parameters also play a key role in maintaining the stability and uniformity of vitamin D in fortified dairy products. Factors such as homogenization, heat treatment, light exposure, and mineral interactions can significantly influence fortification efficiency:

- Homogenization: Promotes even distribution of vitamin D and minimizes phase separation[10].
- Thermal treatment: Vitamin D_3 remains stable during pasteurization and UHT when protected by fat or proteins[9].
- Packaging and light exposure: Opaque or UV-protective containers reduce photo-oxidation losses[22].
- Calcium interactions: Excess calcium may decrease bioaccessibility through the formation of insoluble complexes[30].

Several technological approaches have been explored to improve the stability and bioefficacy of vitamin D in dairy systems (**Figure 1**). These include direct fortification, microencapsulation, nanoemulsions, and protein-based delivery systems, each presenting specific benefits and challenges depending on the product matrix and processing conditions (**Table 1**).

From an industrial perspective, the selection of vitamin D fortification technologies depends not only on their ability to improve stability and bioavailability, but also on factors such as production cost, technological complexity, scalability,

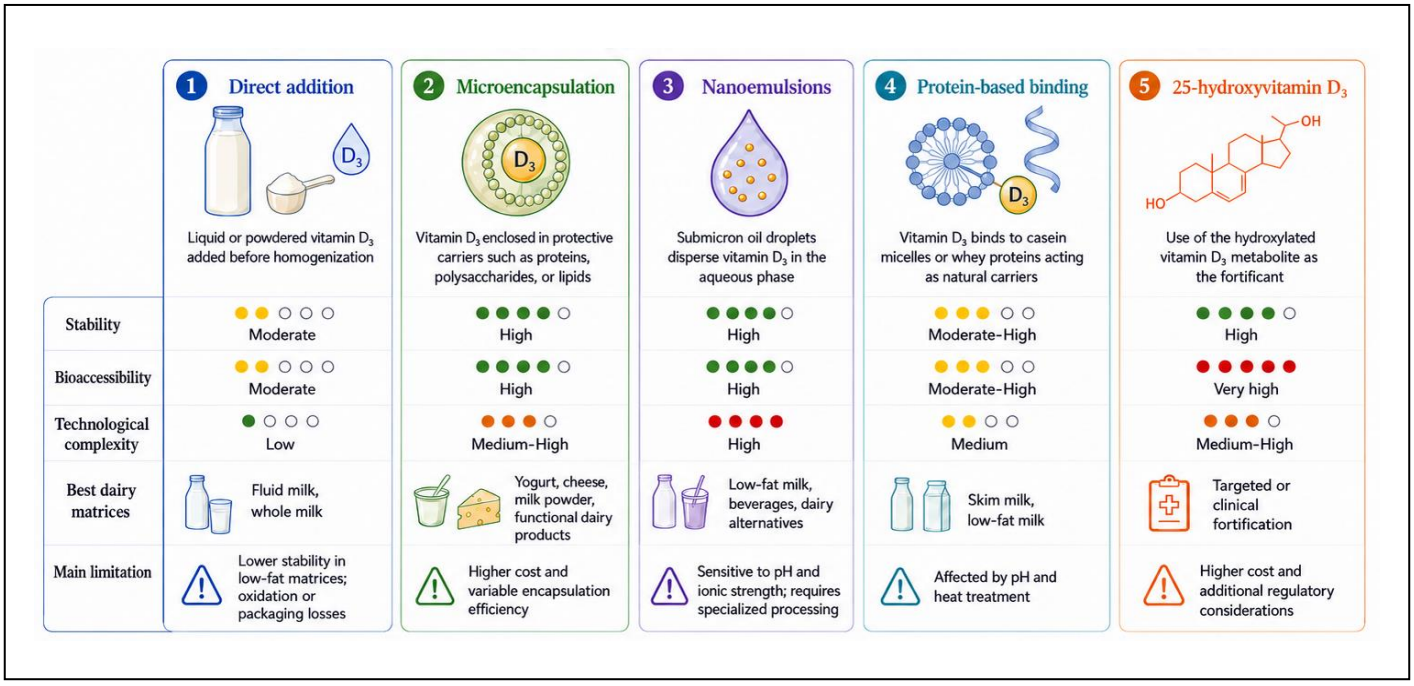

Figure 1. Comparative technological approaches for vitamin D fortification of dairy products.

Table 1. Main fortification technologies.

Technology	Principle	Advantages	Limitations / Considerations	References
Direct addition (vitamin D_3 concentrate)	Addition of liquid or powdered cholecalciferol before homogenization	Simple, cost-effective, widely used in liquid milk.	Possible oxidation or deposition in packaging; limited stability in low-fat matrices.	(9, 10)
Microencapsulation (spray-drying, coacervation, lipid coating)	Encapsulation of vitamin D in a protective carrier (proteins, polysaccharides, or lipids).	Enhances oxidative and photostability; enables controlled release; maintains sensory properties.	Increased cost and complexity; variable encapsulation efficiency.	(10, 11)
Nanoemulsions / oil-in-water emulsions	Formation of submicron oil droplets containing vitamin D dispersed in the aqueous phase.	Improves dispersibility and bioaccessibility; stable under thermal and storage conditions.	Requires high-pressure homogenization; sensitive to pH and ionic strength.	(9, 21)
Use of 25-hydroxyvitamin D_3 (calcifediol)	Fortification with the hydroxylated metabolite of vitamin D_3.	Higher bioavailability and faster serum 25(OH)D response.	Costly; additional regulatory evaluation needed.	(37)
Protein-based binding (casein, β-lactoglobulin)	Non-covalent binding of vitamin D to dairy proteins acting as natural nanocarriers.	Improves solubility and stability in low-fat milk; preserves functionality.	Interaction affected by pH and heat treatment.	(11, 20)
Powdered milk fortification (spray-dry premix)	Addition of vitamin D before or after atomization in milk powder production.	High stability during transport and storage.	Localized heat degradation; requires uniform dispersion.	(10)

and compatibility with existing dairy processing systems. Direct fortification using vitamin D concentrates remains the most widely used strategy due to its low cost, simplicity, and easy integration into conventional dairy processing lines[10,29]. However, in low-fat or highly aqueous matrices, vitamin D stability and homogeneous distribution may be compromised. More advanced approaches, such as microencapsulation and nanoemulsion systems, have demonstrated improved protection against oxidation and enhanced bioaccessibility. Nevertheless, these technologies often require specialized equipment and additional processing steps, increasing production costs and limiting large-scale implementation[9,10]. Protein-based delivery systems using casein micelles or whey proteins represent a promising alternative because they take advantage of naturally occurring dairy structures without major modifications to industrial processes[11,20]. However, further studies are still needed to optimize their scalability and long-term stability under commercial conditions. Therefore, future developments in vitamin D fortification should consider not only nutrient retention and bioavailability, but also technological feasibility and cost-effectiveness for industrial application.

Comparative experience and regulatory framework

There is considerable variation in the availability of vitamin D-fortified foods across countries. Fortification strategies can be classified as mandatory, when they are required and enforced by government policy, or voluntary, when manufacturers decide whether or not to fortify specific products[5]. Fortified foods differ by country and may include margarine, milk, dairy drinks, yogurt, and other commonly consumed products. Overall, countries with mandatory fortification policies tend to show higher vitamin D intakes, with an estimated difference of 2–3 µg/day compared with countries relying on voluntary fortification[31,32].

In North America and Europe, milk and margarine have historically been the most common fortification vehicles. Canada currently maintains mandatory vitamin D fortification of dairy products under the Canadian Food and Drug Regulations[12]. In the United States, by contrast, vitamin D addition to fluid milk is not required unless the product is labeled as fortified; in practice, however, most milk on the market is voluntarily fortified[12]. Across Europe, fortification

Table 2. Dairy vehicles and fortification levels.

Country	Type of vitamin	Vehicles	Dose	Status
USA	Vitamin D_3	Non-fat dry milk Evaporated milk	1.05 µg/100 g 1.05 µg/100 g	Mandatory
		Fluid milk Margarine Yogurt	1.05 µg/100 ml 8.26 µg/100 g 2.23 µg/100 g	Voluntary
Canada	Vitamin D_3	Cow's milk Goat's milk Margarine Yogurt Drinkable yogurt Kefir	2.0 µg/100 ml 2.0 µg/100 ml 26 µg/100 g 3.8-5 µg/100 g 3.9-5.2 µg/100 ml 2.3-2.7 µg/100 ml	Mandatory
Australia	Vitamin D_2 or D_3	Margarine Dried milk	1.0 µg/10 g 2.5 µg/200 ml	Mandatory
		Skim milk Cheese Yoghurt	1.0 µg/200 ml 1.0 µg/25 g 1.0 µg/150 g	Voluntary
Sweden	Vitamin D_2 or D_3	Milk <3% fat Lactose free milk Sour milk <3% fat Margarine	0.95-1.10 µg/100 g 0.95-1.10 µg/100 g 0.75-1.10 µg/100 g 19.5-21.0 µg/100 g	Mandatory
Belgium	Vitamin D_2 or D_3	Margarine	6.0-7.5 µg/100 g	Mandatory
Chile	Vitamin D_3	Fluid milk Dried milk	1.0-1.4 µg/100 ml 10-14 µg/100 g	Mandatory*
Pakistan	Vitamin D_3	Ghee	75-112 µg/kg	Mandatory
Finland	Vitamin D_3	Fluid milk Spreadable fats	1.0 µg/100 ml 20 µg/100 g	Voluntary
Norway	Vitamin D_2 or D_3	Low fat milk Margarine/butter	0.4 µg/100 g 10 µg/100 g	Voluntary

practices remain heterogeneous, with some countries using voluntary industry-led approaches and others implementing national legislation[13]. In Latin America, Chile is currently the only country with a law mandating vitamin D fortification in dairy products, scheduled to take effect in June 2026 (**Table 2**).

The evidence supporting vitamin D fortification of milk and other dairy products is substantial and includes randomized controlled trials as well as population-based modeling studies. These data consistently show that fortified dairy products can improve serum 25(OH)D concentrations and contribute meaningfully to dietary vitamin D intake[31,32]. Recent meta-analyses further support the effectiveness of fortified milk, yogurt, and cheese as vehicles for improving vitamin D status across age groups and geographic settings[33-40]. Thus, while fortified dairy products make an important contribution to vitamin D intake, particularly among children and regular dairy consumers, broader fortification strategies may be needed to reach the population more effectively. In this sense, expanding fortification to other food vehicles, including biofortification approaches, could help improve vitamin D intake and reduce deficiency more widely[41,42].

Health effects of vitamin D-fortified dairy products

WHO and FAO have suggested that micronutrient deficiencies can be addressed through strategies such as increasing dietary diversity, food fortification, and supplementation[43]. Dairy products fortified with vitamin D have demonstrated efficacy and effectiveness in terms of improving vitamin D status in healthy individuals[44] (**Figure 2**).

Evidence in Pediatric and Adolescent Populations

Milk, both liquid and powdered, has been used as a vehicle for vitamin D fortification and has been shown to have health benefits for children and adolescents. Marwaha et al.[45] conducted a double-blind controlled trial in schoolchildren in Delhi, comparing two groups: one that received daily milk fortified with vitamin D_2 (240 IU per 200 mL) and another that received unfortified milk. The

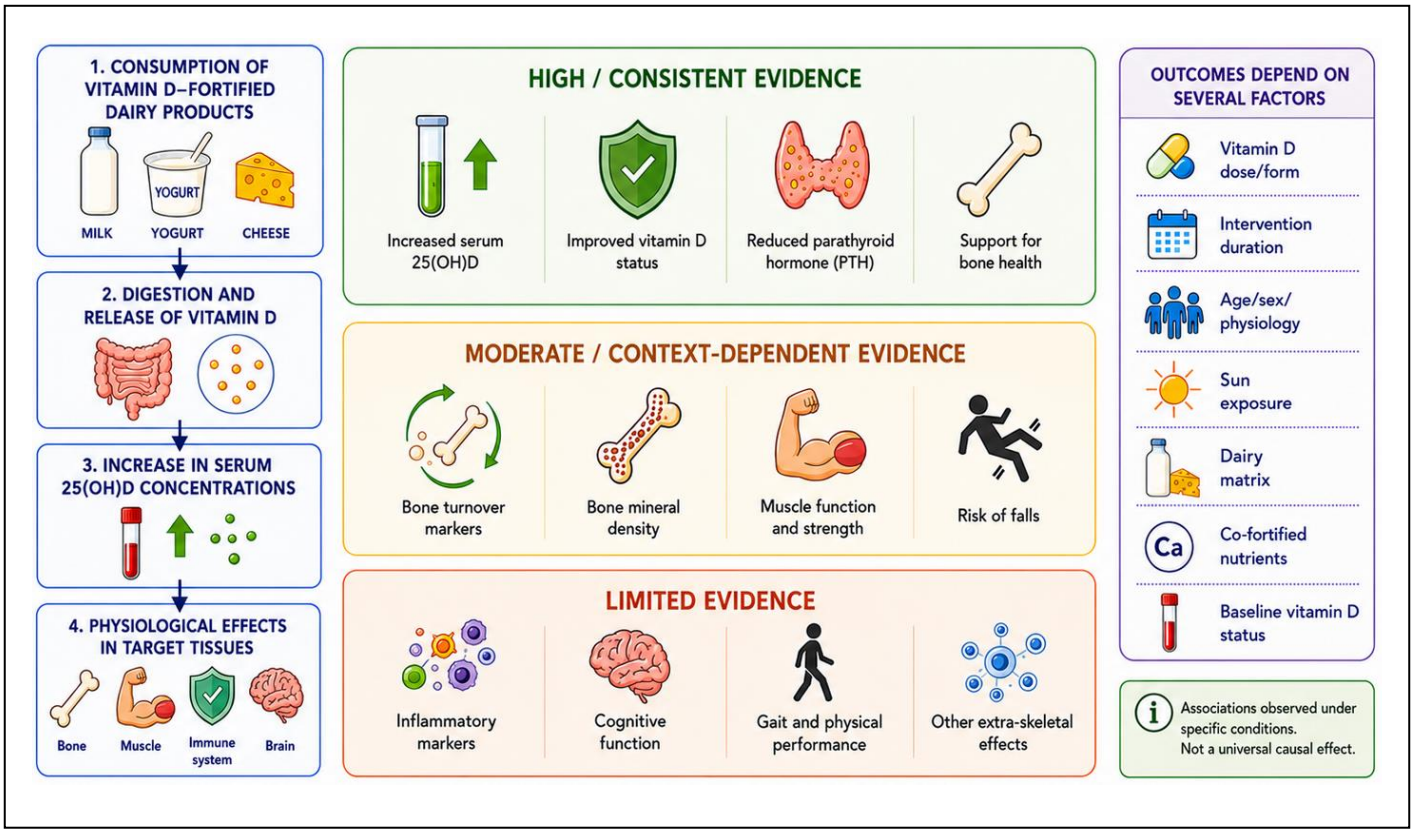

Figure 2. Evidence-based health outcomes associated with vitamin D-fortified dairy product consumption.

authors demonstrated that, although fortified milk intake increased vitamin D levels compared to the control group, the dose used was insufficient to achieve vitamin D sufficiency in children during the winter, due to factors such as the low availability of ultraviolet radiation at that time of year. For their part, Khadgawat et al.[35], conducted a double-blind controlled trial in children aged 10 to 14 years, where participants were randomly assigned to three groups and received daily for 12 weeks either unfortified milk or milk fortified with 600 IU or 1,000 IU of vitamin D.

The results showed that the intake of fortified milk resulted in a significant increase in blood levels of 25(OH)D, with the increase being greater in the group that received the higher dose. Another randomized controlled study conducted by Du et al.[46], in Chinese girls aged 10 to 12 years who received milk fortified with calcium and vitamin D showed that at the end of the 24-month intervention, the girls who consumed milk with vitamin D had a significant increase in serum 25(OH)D levels, reaching a mean of 47.6 ± 23.4 nmol/L, compared to the girls who received milk with calcium only, with a mean value of 17.9 ± 9.0 nmol/L, and the control group with 19.4 ± 10.2 nmol/L. In addition, these girls showed greater increases in size-adjusted total bone mineral content, which correlated positively with the improvement in serum vitamin D levels.

Additionally, Neyestani et al.[47] conducted a randomized controlled clinical trial with children aged 9 to 12 years. Participants were assigned to six groups that received different interventions for 12 weeks: milk fortified with calcium and vitamin D, orange juice fortified with calcium and vitamin D, unfortified milk, unfortified juice, vitamin D and calcium supplements, or a placebo. The authors demonstrated that, although vitamin D supplementation significantly increased blood vitamin D levels, fortified milk was equally effective in improving bone markers and was more acceptable to children.

In the study by Villamor et al.[36], a randomized clinical trial was conducted in Colombia with 80 families, who were randomly assigned to receive either vitamin D_3-fortified skim milk (2,400 IU or 60 µg) or unfortified milk daily for a period of 6 weeks. The population consisted of adolescents aged 12 to 14.5 years and their mothers, who consumed approximately 500 mL of milk per day, and the rest consumed milk freely. The results showed that the daily intake of fortified milk significantly increased serum 25(OH)D concentrations in both groups, with a more pronounced effect in adolescents who had lower initial vitamin D concentrations, darker skin, less sun exposure, and greater compliance with the intake.

Additionally, a study conducted by Öhlund et al.[48] used a double-blind, randomized, placebo-controlled design to assess vitamin D requirements in Swedish children during the winter. Children aged 5 to 7 years from two locations in Sweden (north and south), with different skin tones (light and dark), participated. The subjects received vitamin D supplements in varying daily doses (2, 10, and 25 µg/day) in the form of fortified milk for a period of three months. The results showed that children with light skin achieved sufficient vitamin D concentrations with doses of approximately 20 µg/day, whereas children with dark skin required doses of approximately 28 µg/day to maintain adequate levels. The efficacy of food fortification in

pediatric populations is not uniform; rather, it is strictly modulated by dosage, geographical latitude, and cutaneous phototype.

Evidence suggests that low-dose interventions are often insufficient to maintain vitamin D sufficiency during winter in high-latitude regions due to negligible ultraviolet radiation[45]. Conversely, a robust dose-response relationship emerges when evaluating higher concentrations. Controlled trials indicate that daily doses ranging from 600 IU to 1,000 IU yield significantly greater increments in serum 25(OH)D_3[5]. Critically, the magnitude of this response is dictated by baseline characteristics. Adolescents with lower initial vitamin D concentrations, darker skin pigmentation, and limited sun exposure exhibit the most pronounced benefits from fortified milk intake[36]. Research conducted in Nordic climates further quantifies this variance, suggesting that while children with light skin may achieve sufficiency with approximately 20 µg/day, those with darker skin require doses closer to 28 µg/day to maintain equivalent levels[49]. Nevertheless, substantial discrepancies persist across studies regarding the administered doses, intervention durations, and participants' baseline status. This variability complicates the identification of an optimal fortification threshold and limits the extrapolation of current findings toward standardized, broadly applicable public health guidelines.

Beyond serum markers, fortification has demonstrated a functional impact on bone health, showing positive correlations with size-adjusted bone mineral content[46] and proving as effective as pharmacological supplementation in improving bone markers, often with higher dietary acceptability[47].

Evidence in adult and geriatric populations

Regarding the adult population, McKenna et al.[50] conducted a double-blind, controlled study involving two groups of young adults (under 55 years of age). The participants, who consumed at least 2 liters of milk per week, received milk fortified with vitamin D_3 (12 µg per liter) and calcium (1,525 mg per liter) or unfortified milk. The intervention took place during the winter, and the authors observed that fortified milk intake reduced the seasonal decline in blood 25(OH) D levels by more than 50%, decreasing the decline from 31 nmol/L to 15 nmol/L compared to the control group. In addition, they monitored ionized calcium levels in the blood and creatinine values to assess safety, finding that fortification was safe, with no toxic effects or alterations in renal function parameters.

On the other hand, Keane et al.[49] conducted a controlled, double-blind, randomized study involving 51 adults over 65 years of age with low serum vitamin D levels (less than 12.9 ng/mL). The participants were divided into two groups: one received 500 ml of non-fortified milk daily, and the other received the same amount of milk enriched with 5 mcg (200 IU) of vitamin D for one year. The authors found that fortified milk intake resulted in a significant increase in serum 25(OH)D levels, reaching a mean of 18.5 ng/mL in the group that consumed enriched milk, compared to 12.7 ng/mL in the control group. In addition, they observed an increase in serum calcium levels in the group that consumed fortified milk, highlighting the efficiency of the method for improving vitamin D and calcium levels in this population.

Conversely, Daly et al.[51]conducted a controlled trial in older men (average age 60) who consumed 400 ml of milk fortified with 1000 mg of calcium and 800 IU of vitamin D daily for two years. The results showed that there were no significant changes in blood pressure or lipid levels between the groups, including those with low calcium intake or low vitamin D levels. These results allowed them to conclude that prolonged consumption of milk fortified with these nutrients does not affect blood pressure or lipid profile in healthy older men. In another study by Sharifan et al.[52], a randomized controlled clinical trial was conducted to evaluate the effects of milk fortified with nano-encapsulated vitamin D on systemic inflammation in adults with abdominal obesity. The participants, divided into two groups, consumed 200 mL of milk with 1500 IU of nano-encapsulated vitamin D or plain milk daily for a period of 2.5 months. The results showed that subjects who drank the fortified milk had a significant reduction in inflammatory markers, including neutrophil, lymphocyte, and platelet levels, as well as inflammatory ratios such as the neutrophil-to-lymphocyte ratio (NLR) and the RDW-to-platelet ratio (RPR), compared to the group that consumed unfortified milk.

Finally, regarding the adult female population, Kruger et al.[53] conducted a prospective, controlled study in premenopausal Chinese women residing in Malaysia. The participants were randomly assigned to two groups: one that received vitamin D-fortified milk (15 µg per glass) along with calcium and FOS-Inulin for 52 weeks, and another that drank unfortified milk. The results showed that women who consumed fortified milk had a significant improvement in their vitamin D levels, as well as increases in bone mass at certain sites, compared to those who drank unfortified milk. In addition, both groups achieved reductions in parathyroid hormone (PTH) levels and improvements in grip strength, indicating benefits to bone and muscle health. However, fortified milk was more effective in improving vitamin D levels, which is crucial for bone health in premenopausal women.

In another study, conducted by Green et al.[54], a controlled trial was conducted involving 73 young women from Dunedin, New Zealand. The participants were randomly assigned to two groups: one that consumed non-fortified milk (control group) and another that consumed milk enriched with 5 µg of vitamin D_3 (fortified group) for 12 weeks (from January to April). The results showed that, although there was a significant decrease in 25(OH)D levels in both groups, the participants who drank fortified milk managed to maintain significantly higher 25(OH)D levels than those in the control group. However, the increase in vitamin D levels in the fortified group was not sufficient to completely prevent the seasonal decline in vitamin D. The authors concluded that daily intake of 5 µg of vitamin D_3 in the form of fortified milk can improve vitamin D levels in young women, but that this amount may be insufficient to completely counteract the effects of reduced sun exposure during the winter months in New Zealand.

Another clinical trial, conducted by Kruger et al.[55], studied postmenopausal women in Indonesia and Manila using a randomized controlled intervention design. Participants received milk fortified with high levels of calcium, vitamin D, magnesium, and zinc daily for 16 weeks, compared to a placebo. The study showed that fortified milk intake led to a significant improvement in vitamin D levels, as well as a rapid reduction in PTH concentrations and a decrease in bone turnover markers such as C-telopeptide of type I collagen (CTX), osteocalcin, and procollagen type I N-propeptide (PINP). These results suggest that fortified milk supplementation may be effective in enhancing vitamin D status and reducing bone loss in this population.

Milk derivatives such as cheese and yogurt have also been used as vehicles for vitamin D fortification. An RCT conducted by Bonjour et al.[40] in women with an average age of 85 who were given two 125 g servings of yogurt fortified (FY) with 10 µg/day of vitamin D_3 and 800 mg/day of calcium or control yogurt (CY) providing 280 mg/day of calcium. It showed that on day 56 of the intervention, serum 25(OH)D levels were 25.3 ± 1.8 nmol/L with FY compared to 5.2 ± 2.5 nmol/L with CY.

Another similar RCT conducted by Bonjour et al.[39], in women with a mean age of 73 years who were given FY or FC (fortified with the same doses as in the previous study), showed that on day 84 of the intervention, serum 25(OH)D levels increased from 34.3 ± 2.4 to 56.3 ± 2.4 nmol/L with FY and from 35.0 ± 2.5 to 41.3 ± 3.0 nmol/L in CY. Additionally, these authors[38] conducted an RCT with menopausal women (mean age 61 years) randomized according to serum 25(OH)D levels (low 25-50 nmol/L; high >50-75 nmol/L), who received one and two 125 g servings of yogurt fortified with vitamin D_3 at daily doses of 5 and 10 µg. It was observed that during the 16-week intervention and 8-week follow-up period, 25(OH)D levels increased in both supplemented groups. Additionally, at the end of the intervention, the proportion of participants with 25(OH)D levels ≥50 nmol/L was 37.8%, 54.5%, and 63.6% in the control group, the group supplemented with 5 µg, and the group supplemented with 10 µg, respectively.

Another randomized clinical trial, conducted by Sharifan et al.[52], compared the effects of low-fat yogurt fortified with 1500 IU of nanoencapsulated vitamin D_3 (150 g/day) versus unfortified yogurt (150 g/day) on systemic inflammation in participants with abdominal obesity over a 2.5-month period. It was demonstrated that NLR, platelet/lymphocyte ratio, and RPR values were significantly reduced in the group that received nanoencapsulated vitamin D_3.

Furthermore, a clinical trial conducted by Beauchet et al.[56] examined the effects of yogurt fortified with vitamin D and calcium on spatiotemporal gait parameters, cognitive performance, handgrip strength, and serum 25(OH)D levels in healthy older women. The intervention group consumed fortified yogurt daily (i.e., 400 IU of vitamin D_3 and 800 mg of calcium) for 3 months, while the control group received non-fortified yogurt containing similar amounts of protein, carbohydrates, and lipids, as well as a lower dose of calcium (300 mg) and no vitamin D_3 fortification. The intervention group maintained their overall cognitive performance and serum 25(OH)D concentrations, while in the control group, these parameters worsened. The Mini Mental Status Examination (MMSE) score and serum 25(OH)D concentrations were better in the intervention group compared to the control group. Despite this, there were no significant changes in gait parameters or handgrip strength.

As for cheese, Johnson et al.[57], conducted a crossover clinical trial with two groups (four young adults and four older adults). The subjects received a single acute intake of cheese fortified with vitamin D_2 (5,880 IU per 56.7 g serving) or water enriched with vitamin D_2 (32,750 IU/250 mL). The authors demonstrated that vitamin D_2 absorption was more efficient when administered through cheese. Another clinical trial, conducted by Manios et al.[34], evaluated the effect of consuming 60 g of Gouda-type cheese daily, enriched or not with vitamin D_3, in 79 postmenopausal women for 8 consecutive weeks. The results showed that the intake of cheese enriched with vitamin D_3 (5.7 µg additional daily) was effective in increasing the mean serum concentrations of 25(OH)D in these women.

Additionally, a study by Wagner et al. (58), involved a double-blind, randomized clinical trial conducted with 80 adults recruited through online advertisements at the University of Toronto. Participants, aged 18 to 60, were randomly assigned to six groups that received different treatments: vitamin D-fortified cheeses (cheddar cheese and low-fat cheese), liquid vitamin D supplements taken with or without food, or corresponding placebos. The total dose of vitamin D in the treatments was 28,000 IU per week, equivalent to 4,000 IU daily, for eight weeks. The results showed that vitamin D was equally bioavailable from both fortified cheeses and liquid supplements, regardless of whether it was taken with or without food. In addition, a significant decrease in PTH was observed in the treated groups, indicating improvements in vitamin D status. These findings support the hypothesis that fortified cheese may be an effective and accessible strategy for increasing vitamin D levels in this population.

In adults, dairy fortification serves as a vital tool to mitigate seasonal decline. Evidence shows that fortified milk (12 µg/L) can reduce the winter drop in 25(OH)D levels by more than 50% without compromising safety parameters such as renal function or calcium homeostasis[50]. Nevertheless, in certain demographics like young women in specific latitudes, standard doses (5 µg/day) may still fall short of completely counteracting the effects of reduced sun exposure[54]. In the elderly and postmenopausal populations, the evidence shifts from mere status improvement to systemic health outcomes. Fortified dairy consumption has been linked to significant reductions in PTH levels and bone turnover markers, such as CTX and PINP, thereby reducing the rate of bone loss[53,55]. Moreover, modern delivery methods, such as nano-encapsulated vitamin D in milk and yogurt, have shown promising results in reducing systemic inflammatory markers, such as NLR, and RPR, in adults with abdominal obesity, suggesting a role for fortified dairy in metabolic health[52]. From a safety perspective, long-term interventions in older men have confirmed that high-dose fortification (800 IU) does not adversely affect blood pressure or lipid profiles[51].

Comparative bioavailability across matrices: milk, yogurt, and cheese

The food matrix plays a decisive role in the bioavailability of vitamin D. While milk is the most common vehicle, yogurt and cheese have demonstrated equal or superior efficacy. Yogurt fortification (400–1500 IU) not only maintains 25(OH)D levels but has also been associated with the preservation of cognitive performance in older women compared to non-fortified controls[56]. Dose-dependent studies in menopausal women show that increasing the daily intake from 5 µg to 10 µg significantly raises the proportion of the population achieving vitamin D sufficiency[38-40]. Among dairy derivatives, cheese emerges as a particularly robust vehicle. Comparative trials indicate that vitamin D absorption from fortified cheese is more efficient than from enriched water and shows bioavailability comparable to liquid supplements, regardless of whether it is consumed with or without additional food. This high bioavailability, coupled with significant observed decreases in PTH, supports the use of cheese as an accessible strategy for bone health[34,58].

Finally, a recently published meta-analysis[44] showed that milk, cheese, and yogurt fortified with vitamin D are effective in improving vitamin D status in healthy individuals. Liquid and powdered milk produced significant increases in serum 25(OH)D concentrations, although with high heterogeneity between studies. Similarly, fortified yogurt showed a positive effect with moderate heterogeneity. Fortified cheese showed the greatest increase in 25(OH)D levels, despite the limited number of trials available. Taken together, these results support the use of fortified dairy products as an effective strategy for optimizing vitamin D status.

Conclusion

Vitamin D fortification of dairy products has demonstrated strong potential for improving population vitamin D status, with consistent evidence from randomized controlled trials showing meaningful increases in serum 25(OH)D across diverse age groups and geographic regions. However, significant challenges remain before dairy-based vitamin D fortification can fully contribute to correcting global deficiency rates.

A major limitation is the inconsistency of regulatory frameworks across countries, resulting in a wide variation in fortification levels, food vehicles, and monitoring systems. While some regions have adopted mandatory fortification, most countries still rely on voluntary practices with suboptimal coverage, which limits the public health impact[5]. Moreover, population groups with low dairy intake, including individuals with lactose intolerance, plant-based diets, or limited access to dairy, benefit less from this strategy, underscoring the need for broader fortification approaches and culturally adapted food vehicles[12].

From a technological perspective, ensuring vitamin D stability throughout processing, storage, and distribution continues to be an important challenge. Factors such as oxidation, adsorption into packaging materials, and interactions with minerals and proteins of the dairy matrix may compromise vitamin D retention and bioavailability, particularly in low-fat and plant-based dairy alternatives. Emerging technologies, including nanoemulsions, encapsulation systems, and protein-based carriers, offer promising solutions, but require further evaluation regarding cost-effectiveness, scalability, and regulatory acceptance[20].

Future research should focus on developing next-generation delivery systems that enhance bioefficacy while preserving sensory quality, as well as optimizing processing conditions to minimize degradation. There is also a pressing need for rigorous monitoring programs to ensure compliance with fortification targets and to evaluate long-term effects on nutritional status at the population level. Additionally, more studies are needed in vulnerable groups, such as older adults, pregnant women, and children, particularly in regions with low UVB exposure or high prevalence of deficiency. Expanding fortification policies beyond dairy products, integrating biofortification strategies, and exploring synergistic fortification with other nutrients (e.g., calcium, magnesium, vitamin K) may further enhance public health benefits[59].

Overall, while dairy-based vitamin D fortification represents a scientifically supported and technologically feasible strategy, its full potential requires coordinated regulatory action, innovation in formulation technologies, and robust surveillance systems to reduce global vitamin D deficiency.

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Author contribution

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AB: Conceptualization, Investigation, Data curation, Writing – review and editing.

FPB: Investigation, Data curation, Writing – original draft.

RV: Conceptualization, Data curation, Validation.

CE: Data curation, Visualization.

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Conflict of interest

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AI statement

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