

FORTIFIED FOODS WITH VITAMIN D AND ZINC

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ABSTRACT

Hidden hunger, also known as micronutrient deficiencies, remains an important global public health issue despite improvements in overall food security. Among essential micronutrients, vitamin D and zinc have important roles in immune regulation, skeletal development, and metabolic functions. But deficiencies in these nutrients are prevalent particularly among vulnerable groups such as children, pregnant women, and the elderly. This review examines the physiological functions, deficiency epidemiology, health consequences, dietary sources, and the necessity of food fortification with vitamin D and zinc. Furthermore, it discusses the synergistic effects of vitamin D and zinc, and technological methods and challenges for fortifying foods with both vitamin D and zinc. Future research should focus on developing new encapsulation technologies, optimizing nutrient delivery systems, and undertaking long-term clinical trials to validate the health benefits of new co-fortified foods.

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1. Introduction

1.1 Research Background

Most people in the world are no longer troubled by starvation. People's diets have sufficient carbohydrates, proteins and fats. However, more people suffer from not enough vitamins and minerals, which is referred to as hidden hunger. It can be a significant issue because hidden hunger is imperceptible and can cause serious consequences. For example, around 500,000 vitamin A deficient children go blind per year. There are over 2 billion people affected by hidden hunger.

Micronutrients, including vitamins and minerals, are important in healthy diets. They have an important role in maintaining a healthy status for diverse populations across age, gender and geographic regions. Most of them are essential for numerous physiological processes including immune function, skeletal development and cellular metabolism.

This paper will review fortified foods specifically with vitamin D and zinc. These two micronutrients have high rates of inadequacy especially in vulnerable groups such as children, pregnant women and elders [1][2].

There are many foods that are rich in vitamin D and zinc. For example, 100 g of salmon has 600 international units (IU) of vitamin D and 100 g of pork liver has 4 mg of zinc. Although many foods are good sources of vitamin D and zinc, some people cannot get enough with their routine diets. The reasons are a lack of food availability or consumption of low nutrient density foods. Therefore, fortified foods with vitamin D and zinc become necessary.

Food fortification has become an effective and scalable intervention. Studies have shown that vitamin D-fortified foods significantly improve serum 25-hydroxyvitamin D (25(OH)D) levels, even in community-based settings with diverse baseline characteristics [3]. Similarly, zinc fortification, whether alone or with multiple micronutrients, has shown improvements in serum zinc levels, child weight, memory, and a reduction in incidences of diarrhea [4]. Despite some inconsistencies in outcomes, fortification is considered safe, cost-effective, and accessible for risky populations. However, knowledge gaps remain regarding optimal fortification levels, bioavailability, and long-term functional outcomes which need to be determined with further research [1].

1.2 Overview of the Health Benefits of Vitamin D and Zinc

Vitamin D is needed for bone health and calcium metabolism. It has been shown to be a pleiotropic hormone with multiple physiological functions. Its active form, 1,25-dihydroxyvitamin D, not only supports skeletal health but also influences immune function, cardiovascular integrity, cancer prevention and metabolic regulation [5].

Zinc is an essential trace mineral needed for numerous human physiological processes including enzyme function, immune regulation, growth and tissue repair. As a cofactor in over 300 enzymes, it has an important role in cell division, DNA/RNA synthesis, and antioxidative defenses [6].

1.3 Deficiency Status of Vitamin D and Zinc and Their Public Health

Implications

Vitamin D and zinc deficiencies represent significant global public health challenges. Vitamin D deficiency is closely associated with deteriorating bone health, impaired immune function, and increased risk of chronic diseases. The severity of this issue has received attention, particularly among vulnerable populations such as the elderly, pregnant women, and children [7].

Zinc, an essential trace element, has important roles in immune function, growth and development, and gene expression. Zinc deficiency can lead to growth retardation in children, poor immune system, and pregnancy complications [8].

Although food fortification and dietary supplements have improved micronutrient intake to some extent, inadequate intake of vitamin D and zinc remains prevalent, especially among populations in economically disadvantaged regions or those with limited dietary diversity.

Public health institutions have recognized the severity of vitamin D and zinc deficiencies, advocating for increased nutritional surveillance and effective intervention strategies [9]. However, considerable knowledge gaps remain regarding the specific mechanisms, dose-response relationships, and long-term health impacts of these deficiencies. Further research is needed to clarify their effects on various populations and to develop effective, safe, and sustainable supplementation strategies. Addressing these issues would not only improve overall public health but also reduce associated healthcare burdens, thereby promoting long-term socioeconomic stability and development.

2. Physiological Functions and Health Benefits of Vitamin D and Zinc

2.1 Physiological Functions of Vitamin D

Vitamin D is essential in maintaining calcium and phosphate homeostasis promoting bone mineralization and preventing rickets in children and osteomalacia in adults [10].

Vitamin D also has a preventive role in reducing bone breaking by limiting fall risk through improved neuromuscular performance [11].

Vitamin D can improve the immune system of people through binding to its receptors that are expressed in macrophages, dendritic cells, T cells and B cells. In patients with chronic hepatitis B, vitamin D deficiency correlates with a reduction in CD4⁺ T cells and an increase in CD8⁺ T cells which impairs antiviral immunity. This suggests that vitamin D may support immune homeostasis by modulating lymphocyte profiles and antibody production [12].

Vitamin D contributes significantly to cardiovascular and metabolic health through multiple biological mechanisms. It can enhance endothelial function and glucose homeostasis, reduce oxidative stress, inflammation, and thrombosis, and regulate calcium and lipoprotein metabolism [13]. Low concentrations of serum vitamin D in humans have been epidemiologically associated with increased risks of coronary artery disease, atherosclerosis and metabolic syndrome [14]. According to large randomized controlled trials vitamin D indeed can give population benefits with respect to these aspects [14].

Vitamin D has the potential to prevent cancer and endocrine diseases through mechanisms involving modulation of cell proliferation, differentiation, and apoptosis. There is increasing evidence that sufficient vitamin D may reduce the risk of several

cancers particularly colorectal cancer [14]. Moreover, vitamin D has an important role in improving insulin sensitivity, reducing insulin resistance, and modulating metabolic pathways involved in obesity [15]. Low serum vitamin D levels have been consistently linked with increased incidence of type 2 diabetes and metabolic disorders [16].

2.2 Physiological Functions of Zinc

Zinc is essential for immune function and antiviral defenses. It supports the development and function of immune cells such as macrophages, neutrophils, and T cells. Zinc deficiency leads to thymic atrophy, lymphopenia, and impaired cytokine signaling. Zinc also has a direct antiviral activity, interfering with the replication of several viruses and enhancing interferon-stimulated gene responses [17].

Zinc has an important role in anti-inflammation and chronic disease modulation. In patients with cardiovascular disease (CVD) and COVID-19 comorbidity, zinc supplementation helps modulate the angiotensin-converting enzyme 2 (ACE2), a zinc metalloenzyme that the virus needs to combine with it to invade human body. Thereby potentially reducing SARS-CoV-2 viral replication while supporting vascular protection [18].

Zinc contributes significantly to tissue repair through its roles in collagen synthesis, epithelial cell proliferation, and antioxidant protection. Clinical trials have shown that zinc supplementation reduces the severity and duration of oral mucositis in patients undergoing chemoradiotherapy for head and neck cancers [19].

Zinc is particularly important in infancy and early childhood. Supplementation in Tanzanian infants showed metabolic changes in amino acid and fatty acid pathways,

suggesting zinc's influence on nutritional status and the trajectory of growth. Although metabolic shifts were subtle, clinical improvements in infection resistance and growth were evident [20].

Zinc is essential for the activity of antioxidant enzymes such as superoxide dismutase (SOD) helping to combat oxidative stress and protect cellular integrity. It also stabilizes cellular membranes and DNA structures, especially in organs with high metabolic activity such as the liver and brain [21].

2.3 Synergistic Effects and Interactions Between Vitamin D and Zinc

The interactions between micronutrients are an important aspect of human nutrition, influencing absorption, metabolism, and physiological outcomes. Vitamin D and zinc have complementary roles in immune function, bone health, and cellular signaling pathways.

Vitamin D and zinc have different roles in many biochemical pathways, but they have synergistic effects in immune regulation, cellular homeostasis and bone metabolism.

These two micronutrients have complementary roles in modulating both innate and adaptive immune responses, and their co-deficiency often exacerbates health complications in vulnerable populations.

Mechanistically, vitamin D acts through the vitamin D receptor (VDR), which is expressed in almost all immune cells and regulates the transcription of immune-related genes. Zinc, on the other hand, serves as a structural component for over 2,500 transcription factors and is important in stabilizing DNA, RNA, and cell membranes. Zinc deficiency can impair VDR function and thereby attenuate vitamin D-mediated

gene expression. On the other hand, vitamin D has been observed to modulate zinc transporter expression, including Zrt- and Irt-like Protein (ZIP) and Zinc Transporter (ZnT) families, which are essential for intracellular zinc homeostasis [22].

Both zinc and vitamin D contribute to maintaining immune tolerance, particularly through balancing Th17/Treg and Th1/Th2 responses. Zinc increases the expansion of regulatory T cells (Treg), while vitamin D promotes Treg stability and suppresses pro-inflammatory Th17 cells. Their co-administration in autoimmune disease models such as multiple sclerosis significantly reduced inflammation, suggesting an immunological synergy [8].

In the context of bone metabolism, hypophosphatasia (HPP) patients showed that both vitamin D and zinc are indispensable [23]. Zinc is a cofactor for tissue non-specific alkaline phosphatase (TNSALP), an important enzyme for bone mineralization, while vitamin D increases calcium absorption and bone matrix formation. Supplementation of both nutrients normalized their serum levels without adversely affecting calcium or phosphate metabolism, indicating their safe and effective applications with skeletal disorders.

Furthermore, zinc and vitamin D appear to have overlapping anti-inflammatory roles. Zinc can inhibit nuclear factor- κ B (NF- κ B) signaling, a major pathway in inflammation, while vitamin D downregulates pro-inflammatory cytokines such as IL-6 and TNF- α . This dual modulation is particularly beneficial in reducing “cytokine storm” responses seen with viral infections [24] [25].

Taken together, the interactions between vitamin D and zinc represent a biologically plausible and clinically relevant area of intervention. Co-supplementation strategies

may provide greater benefits than single nutrient interventions, especially with conditions characterized by immune dysregulation, chronic inflammation, or bone fragility.

3. Epidemiology of Vitamin D and Zinc Deficiency

3.1 Global Prevalence of Vitamin D and Zinc Deficiency

Vitamin D deficiency is prevalent worldwide. Serum 25-hydroxyvitamin D [25(OH)D] levels <20 ng/mL have been observed in up to 70–75% of UK adults during winter and 18–40% of adults in southern U.S. states during low sunlight seasons [3]. In the National Health and Nutrition Examination Survey (NHANES) 2003–2006, it was found that the dietary intake of vitamin D and zinc for U.S. residents >2 years old was deficient [26]. Vitamin D intake among Americans is generally insufficient. Entire populations of people who only rely on naturally occurring food sources for vitamin D have an inadequate vitamin D intake. They are all below the Estimated Average Requirement (EAR), which is the average daily nutrient intake level estimated to meet the requirement of half of healthy individuals. Even with the contribution of fortified foods, 93% of the population failed to meet the EAR for vitamin D. With dietary supplements, only 31% of individuals can meet the requirements. These data indicate that vitamin D is one of the most deficient nutrients in the U.S. population. Americans have a high dependence on food fortification and dietary supplements to meet recommended intake levels. The causes are multifactorial, including reduced dietary intake, lack of sun exposure, and aging-related metabolic inefficiencies [27].

Longitudinal analysis of NHANES data from 1988–1994 and 2000–2004 showed that

the serum 25(OH)D levels of U.S. adults declined significantly over time. This trend was not entirely due to assay variation; part of the real decline was attributed to increased BMI, decreased milk intake, and increased sun-protective behaviors such as staying indoors or using sunscreen. These behavioral and physiological changes have collectively contributed to the deteriorating vitamin D status in the U.S. population, especially among adults aged 20-59 [28].

Zinc deficiency is a globally recognized nutritional concern affecting an estimated 17% of the global population that is at risk of inadequate zinc intake due to poor diet diversity and low animal food consumption [29]. The deficiency is particularly high in South Asia and Sub-Saharan Africa, where soil zinc depletion and cereal-based diets with high phytate content inhibit zinc absorption. However, this is not solely a developing world issue. In high-income countries, zinc deficiency is also widespread among specific populations, such as the elderly, vegetarians, patients with chronic diseases, and those with malabsorption conditions [17]. According to the World Health Organization, approximately 30% of populations in developing countries may have insufficient zinc intake based on national food supply data and the prevalence of stunting [30]. Among patients with chronic liver disease (CLD), the prevalence of zinc deficiency exceeds 50% and is closely associated with hepatic encephalopathy, immunosuppression, and increased mortality [6]. Furthermore, screening for zinc deficiency is difficult because plasma zinc levels are not always reliable due to inflammation and redistribution with certain conditions. Therefore, the real ratio of zinc deficiency may be higher than suggested by these data [31].

3.2 Deficiency Status and Risk Factors in Different Populations (Children, Pregnant Women, the Elderly)

Vitamin D is an important micronutrient at every stage of life. Meanwhile, vitamin D is easy to be deficient across populations.

In children, a systematic review from Indonesia reported a 33% prevalence of vitamin D deficiency underscoring a public health emergency even in sun-rich regions near the equator [32]. Moreover, obese children are particularly at risk, as vitamin D is sequestered in adipose tissue, reducing its bioavailability [33].

Among pregnant women, vitamin D status has an important role in fetal skeletal formation, immune programming, and pregnancy outcomes [34]. In Indonesia, over 60% of pregnant women were vitamin D deficient, a condition strongly associated with socioeconomic status and lack of supplementation [32]. Similarly, a large cohort study from China found that only 26% of pregnant women had sufficient vitamin D levels, and underweight status was a significant risk factor for a deficiency [34].

For elderly people, the vitamin D deficiency often relates to reduced dermal synthesis, limited outdoor activity, and decreased dietary intake. In China, surveys showed that 58% of people over 60 had vitamin D insufficiency, with older women being particularly at risk [35]. For Europeans, up to 30% of elderly adults in Europe have inadequate vitamin D levels, with women showing higher deficiency rates than men [36].

Zinc is also easily deficient across various population groups. Infants, young children, and pregnant women in low- and middle-income countries are most affected [37].

In children, a nationally representative survey in Nepal reported that 23% of children had serum zinc concentrations below the recommended threshold suggesting growth retardation of children [38]. Overall, zinc deficiency contributes to approximately 450,000 child deaths annually mainly because of the associated diarrhea and pneumonia [39].

Among pregnant women, the physiological demands of pregnancy increase zinc requirements, and deficiencies have been associated with adverse outcomes such as preterm birth, low birth weight, and impaired fetal development. A large-scale Japanese study involving over 28,000 participants identified pregnant women as being significantly more prone to zinc deficiency [40]. Studies from Ethiopia showed that low-income and rural-residing pregnant women were over six times more likely to be zinc deficient [41].

In the elderly population, zinc deficiency usually occurs because of decreased dietary intake, reduced gastrointestinal absorption, and the presence of chronic illnesses. A nationwide database study from Japan demonstrated a 30% increase in the odds of zinc deficiency per decade of age, with individuals whose BMI falls below 25, a range generally considered healthy, showing a higher risk.[42].

3.3 Long-Term Health Consequences of Vitamin D and Zinc Deficiency

Long-term deficiencies of vitamin D and zinc can lead to persistent health consequences across multiple physiological systems.

Chronic vitamin D deficiency has been associated with increased risks of osteoporosis, fractures, autoimmune disorders, and certain cancers, as well as metabolic and cardiovascular diseases especially in postmenopausal women [16].

A narrative review indicated that prolonged deficiency during important periods such as pregnancy or early childhood can impair fetal bone mineralization and neurodevelopment, increasing the risk of chronic disease later in life. According to the review, for pregnant women, serum 25-hydroxyvitamin D levels <20 ng/mL are classified as deficient. It can lead to higher risks of preeclampsia, preterm birth, gestational diabetes, and intrauterine growth restriction. For the developing fetus, inadequate maternal vitamin D status can disrupt skeletal mineralization and lead to small-for-gestational-age infants [43]. A study involving more than 3000 participants found that vitamin D deficiency increased the risk of preeclampsia by 79% and gestational diabetes by 49% [44]. For offsprings, low maternal vitamin D levels have been linked to a >40% risk of childhood asthma and impaired lung function [45].

Beyond bone health, recent results suggested that vitamin D has an important role in cardiovascular, neurocognitive, and autoimmune regulation. For example, in patients with multiple sclerosis (MS), lower vitamin D levels were significantly linked to increased long-term risks of cardiovascular complications. Patients with deficient serum 25(OH)D levels (<12 ng/mL) had a 32% higher incidence of major adverse cardiovascular events (MACE), and those with inadequate levels (13-20 ng/mL) had a 29% higher risk, compared to patients with adequate vitamin D levels [46].

For zinc, long-term deficiency can impair immune competence, leading to increased frequency and severity of respiratory infections such as pneumonia, especially among children and the elderly.

For respiratory infections, a 2024 study reported that zinc-deficient individuals had a 2.5-fold increased risk of severe lower respiratory tract infections compared to zinc-sufficient counterparts [47]. In children 2-24 months, a randomized controlled trial in India reported that zinc supplementation reduced the duration of severe pneumonia by 20%, and the incidence of treatment failure was 33% lower among those children receiving zinc [48].

Chronic zinc deficiency has also been associated with cognitive impairment, mood disorders and neurodegenerative processes. Prasad's study showed that elderly individuals with marginal zinc intake had significantly poorer memory performance and were more prone to depressive symptoms and inflammatory markers associated with cognitive decline [49].

Moreover, chronic zinc deficiency has been implicated in the pathogenesis of chronic conditions such as type 2 diabetes and atherosclerosis. A longitudinal study found that individuals in the lowest zinc quartile had a 1.7-fold increased risk of developing metabolic syndrome over 10 years [50].

4. Dietary Sources of Vitamin D and Zinc and the Necessity of Food Fortification

Vitamin D is naturally present in only a limited number of foods, making it difficult for many individuals to meet recommended intake levels through diet alone.

Food	Vitamin D ($\mu\text{g}/100\text{ g}$)
Eel	26
Fish, Average, Grilled	14
Salmon Fillet, Oven-Baked	9
Egg Yolk, Fried	7
Mushrooms, Blanched	6
Egg	3
Liver, Beef	1

Table 1. Vitamin D content of some foods [51]

The data for vitamin D food shows that fish are generally the best source of vitamin D. But people consume less fish than needed to meet the requirements, especially people who live in inland area. Data from North American and European population surveys showed that median daily intakes are well below the EAR of 10 $\mu\text{g}/\text{day}$. In the U.S., median intakes are approximately 6 $\mu\text{g}/\text{day}$ for children and similarly for adults, while Canadian adults consume even less, with daily medians ranging from 3.5 to 5.7 μg depending on age and gender [52].

As a result, food fortification has become a highly effective and equitable strategy to improve population vitamin D status. A systematic review showed that vitamin D fortification of staple foods such as dairy products, bread, and cereals led to mean increases of 6-10 ng/mL in serum 25(OH)D concentrations, which significantly reduced the proportion of individuals with deficiencies across all age groups [53]. In Finland, they implemented a nationwide vitamin D fortification policy in 2003

enriching milk and margarines. Within five years, the prevalence of serum 25(OH)D of <20 ng/mL in adults dropped from 50% to just 10% [54].

Although zinc is found in a variety of foods, its bioavailability varies significantly making it challenging for populations relying on plant-based diets to meet recommended intake levels through diet alone.

Food	Zinc (mg/100 g)
Cooked Oysters	45
Beef Chuck Roast	9
Lamb Leg (Roasted)	4
Chicken Thigh (Roasted)	3
Crab (Cooked)	3
Cheddar Cheese	3
Whole Wheat Bread	1
Brown Rice (Cooked)	0.5
Milk (Whole)	0.5

Table 2. Zinc content of some foods [55]

Zinc is usually found in animal-sourced foods such as red meat and shellfish. And plant-based foods often have low bioavailability due to a high phytate content, which is a known inhibitor of zinc absorption [56]. Cereal-based diets dominate in low and middle-income countries, making zinc deficiency prevalent. According to a WHO report, nearly 17% of the world's population is at risk of inadequate zinc intake, with the prevalence exceeding 25% in South Asia and Sub-Saharan Africa [57].

Given the global burden, zinc fortification of staple foods is considered a cost-effective, sustainable strategy to improve intake. Zinc fortification of flour and complementary foods in low-income settings led to reductions in diarrhea incidence by 18% and improved linear growth by 0.37 cm/month in young children [58].

5. Development of Vitamin D and Zinc Fortified Foods

5.1 Common Categories of Fortified Foods

Food	Fortification details
Milk	Fluid milk is typically fortified with vitamin D ₃ at 400 IU/L ($\approx 10 \mu\text{g/L}$) using oil-based solutions added during homogenization or pre-pasteurization blending.
Yogurt	Fortified with 5-10 μg vitamin D ₃ /125 g serving, often using microencapsulation or emulsion-based delivery systems to preserve stability.
Cheese	Vitamin D added during production as oil-soluble D ₃ emulsions, 5 μg /30 g slice.
Dark Chocolate	Fortified by incorporating 5 μg vitamin D ₃ /serving into the lipid matrix during conching. Sensory studies showed no alteration in flavor.
Egg	Biofortification through hen feed enriched with vitamin D ₃ , yields 1-2 μg /yolk.
Orange Juice	Fortified with 2.5-5 μg /240 mL using nanoemulsions to

	ensure water-soluble delivery.
Cereal	Vitamin D ₃ in powdered form is spray-coated post-baking, 2.5-10 µg/portion.
Beef	Biofortification through cattle feed supplementation, muscle content raised to 0.7 µg/100 g.

Table 3. Foods fortified with vitamin D [59][60][61][62][63][64][65]

Food	Fortification details
Wheat Flour	Fortified with zinc oxide or zinc sulfate during milling, commonly 30–60 mg/kg.
Rice	Fortified with zinc using extrusion, 9 mg/kg.
Milk	Liquid milk enriched with zinc lactate or gluconate, typically 1-2 mg/250 mL.
Infant Formula	Zinc added as premix of zinc sulfate. Standardized dose is 5 mg/L.

Table 4. Foods fortified with zinc [66][67][68][69]

5.2 Methods and Technologies for Food Fortification

Direct addition is the most common method of vitamin D fortification. Typically, vitamin D is added to food products during processing. Vitamin D₃ (cholecalciferol) is often preferred over D₂ (ergocalciferol) due to its greater efficacy in raising serum 25(OH)D levels [70]. Therefore, in industrial applications, vitamin D₃ is usually added in the form of an oil-based emulsion or an alcoholic/propylene glycol solution. For

liquid products, vitamin D should be added before homogenization or pasteurization to ensure even distribution and prevent phase separation. In powdered products, vitamin D can be blended directly with other dry ingredients [71]. While this approach is simple and cost-effective, it requires careful handling due to vitamin D's sensitivity to light, heat, and oxygen, which can affect the product's stability during storage [72].

Vitamin D emulsification has been adopted with functional foods to enhance solubility and bioavailability by encapsulating fat-soluble vitamin D in an oil-in-water emulsion system, especially in water-based systems such as plant-based beverages and juices. Emulsifiers such as lecithin and Tween 80 are commonly used, and high-shear or ultrasonic emulsification techniques help maintain stability with processing conditions [73].

Microencapsulation is another popular method for protecting and delivering vitamin D in foods. This method involves encapsulating vitamin D in microcapsules using wall materials such as gelatin, maltodextrin, or gum Arabic. It effectively prevents degradation of vitamin D during storage and processing and improves the sensory properties of the final food product. These microcapsules can be prepared using spray drying, freeze-drying, or coacervation techniques and the microcapsules can be added directly into yogurts, cheeses, baked goods, and nutrition bars. An important advantage is the ability to control the release of vitamin D and enhance its stability with varying pH and light conditions [74].

There is a special method to fortify vitamin D in eggs. The content of vitamin D in eggs can be increased by changing the diet of hens. Feeding hens with a diet

containing 5,000 IU/kg of vitamin D₃ can significantly increase egg yolk vitamin D₃ content from 0.6 to 7.5 µg/egg [75].

Direct addition is one of the most used techniques for zinc fortification. It is suitable for both powdered foods and liquid products. In powdered forms, zinc is commonly added by dry mixing in zinc oxide (ZnO) or zinc sulfate (ZnSO₄), typically at levels ranging from 30 to 60 mg/kg. For liquid foods, more soluble salts such as zinc lactate (Zn(C₃H₅O₃)₂) or zinc gluconate (Zn(C₆H₁₁O₇)₂) are often used to avoid precipitation. This method is technically mature and cost-effective, although special attention must be paid to factors such as pH and the presence of emulsifiers, which may affect zinc solubility and bioavailability [76].

Spray drying and coating is another method to fortify foods with zinc. This technique involves encapsulating zinc salts within carriers such as starch, gelatin, or lipids, followed by spray drying to produce microparticles. These are easy to incorporate into cereal products, nutritional powders, instant rice, or breakfast cereals. The coating helps prevent zinc from absorbing moisture and clumping during storage or reacting with other minerals, and it also improves the sensory qualities of the final product. This method is commonly used in fortified breakfast cereals, infant foods, and enriched biscuits.

5.3 Stability and Interactions of Vitamin D and Zinc in Foods

Among foods that are fortified with both zinc and vitamin D are, for example, infant formula milk powder (Abbott, Nestle) and milk (Fonterra, New Zealand). Many

foods cannot be fortified with both zinc and vitamin D simultaneously because of their chemical properties and delivery requirements.

Vitamin D₃, which is the most common form of vitamin D fortification, is lipophilic and structurally sensitive to heat, light, and oxidation. It often shows poor stability in aqueous or heat-processed systems. However, when embedded in protective matrices like nanoemulsions, liposomes, or microcapsules, its stability can be significantly improved. For example, encapsulated vitamin D₃ showed <10% degradation in fortified UHT milk stored for 12 wk at 4°C, even after pasteurization at 138°C. These encapsulation systems form physical barriers that not only prevent oxidation but also allow controlled nutrient release in the gastrointestinal tract [77].

On the other hand, zinc is chemically more stable. When zinc is co-delivered with dairy components such as casein phosphopeptides or citrate, zinc absorption improves significantly by forming soluble complexes that facilitate intestinal uptake. Adding casein phosphopeptides to a low-phytate rice-based meal can increase zinc absorption from 15 ± 1 to $18 \pm 1\%$, representing a relative enhancement of approximately 18% [78]. However, zinc has limited bioavailability in the presence of dietary inhibitors such as phytates. Phytates are abundant in grains, legumes and seeds. They can form stable and insoluble zinc-phytate complexes in human intestines. The solubility of zinc phytate was five orders of magnitude lower than that of zinc citrate showing the importance of reducing phytate [79].

The co-fortification of foods with vitamin D and zinc involves complex interactions at the chemical and matrix levels, often leading to significant formulation challenges.

A major interaction challenge arises from the differences in solubility behavior. Vitamin D tends to partition into the lipid phase of emulsified systems, whereas zinc ions remain in the aqueous phase. This can lead to localized ionic imbalances that promote aggregation or coalescence of emulsified droplets, potentially destabilizing the fortified food product over time [80]. Moreover, zinc ions may catalyze oxidative degradation processes, especially in systems with unsaturated lipid carriers for vitamin D, thus decreasing both nutrients' stability during storage [81].

To mitigate these adverse interactions, encapsulation technologies such as separate microcapsules for each nutrient, or the use of protective matrices combining proteins and polysaccharides, are recommended. Careful adjustment of pH, ionic strength, and the sequential addition of micronutrients during food processing are also important to preserve the bioavailability and stability of both vitamin D and zinc [78].

6. Markets and Regulations of Vitamin D and Zinc Fortified Foods

6.1 Global Market Trends

The global market for foods simultaneously fortified with both vitamin D and zinc remains a niche but a rapidly growing segment within the broader functional and fortified foods industry. Driven by increasing consumer demand for immune-boosting and bone-health products post-COVID-19, manufacturers are increasingly combining these two nutrients into single formulations to address synergistically multiple health concerns [82].

Vitamin D fortified products, particularly dairy beverages, breakfast cereals, and plant-based milks, have seen increased adoption rates post-pandemic. The vitamin D

fortified foods sector has been expanding at an estimated compound annual growth rate of approximately 7% over the past decade. This growth has been due to public health campaigns and regulatory initiatives promoting vitamin D fortification in countries such as the U.S., Canada, Finland, and India [83].

Zinc-fortified foods, on the other hand, are growing within the functional food and nutraceutical categories. The zinc supplementation market alone is expected to reach USD 23 billion by 2028, growing at a compound annual growth rate of 7.2%, with zinc-enriched cereals, dairy products, and immunity-boosting snacks becoming more popular [84].

Mintel's Global New Product Database (GNPD) reports that between 2019 and 2023, the number of product launches simultaneously fortified with both vitamin D and zinc grew by approximately 8% annually, particularly in the Asia-Pacific and North America [85].

Although specific global market data for foods co-fortified with both nutrients remains limited, consumers are increasingly selecting clean label, plant-based, and sustainably sourced fortified foods. This requires manufacturers to innovate with natural emulsifiers, bio-based microencapsulation, and synergistic fortification strategies that combine vitamin D and zinc into single formulation.

6.2 Regulations and Standards for Food Fortification in the U.S.

The Federal Food, Drug, and Cosmetic Act (FFDCA), enacted in 1938, is the foundational law for food safety in the U.S. This act authorizes the Food and Drug Administration (FDA) to regulate food, drugs, and cosmetics, specifying which

substances may be added to foods, whether food additives are permitted, in which types of foods they can be used, and the allowed usage levels. Therefore, whether vitamin D and zinc can be used for food fortification, how much can be added, and how labeling requirements are determined are all governed based on the principles established by the FFDCAs as amended.

In the U.S. Title 21 of the Code of Federal Regulations (21 CFR) has the regulations regarding the safe fortification of foods with vitamin D and zinc. Specifically, Parts 184–186 list the nutrients recognized as safe for direct addition to foods. These regulations, i.e., 21 CFR 184.1950, specify the permissible usage levels and conditions for adding vitamin D₃ to fortified milk, breakfast cereals, and other foods. Meanwhile, 21 CFR 184.1298 designates zinc oxide as an approved source of zinc for food fortification and recognizes it as Generally Recognized as Safe (GRAS).

Vitamin D fortified foods need to obey the 21 CFR rules. The primary forms of vitamin D used for food fortification are vitamin D₂ and vitamin D₃. The maximum fortification levels of vitamin D vary for different food categories. Milk and plant-based milk alternatives are allowed to be fortified with up to 400 IU of vitamin D/quart, a traditional standard established to prevent rickets. For breakfast cereals, the fortification limit is up to 350 IU/100 g, giving manufacturers more formulation flexibility to achieve nutritional targets, though requiring careful control of total intake. Orange juice can be fortified with up to 100 IU of vitamin D/240 mL. However, only food products that meet the FDA's fortification guidelines and receive explicit approval, such as specific brands or formulations of orange juice, are permitted to include added vitamin D. For infant formulas, regulations mandate a vitamin D

content of 40-100 IU/100 kilocalories, a compulsory standard to ensure that the essential nutritional needs of infants are met.

Approved forms of zinc for food fortification include zinc oxide, zinc sulfate, and zinc gluconate. Ready-to-eat breakfast cereals are typically fortified with 3.8 to 15 mg of zinc/serving, ensuring a significant contribution to the Daily Value without exceeding safe intake levels. Infant formulas are regulated to contain between 0.5 and 1.5 mg of zinc/100 kilocalories.

There is no special legal provision in the current U.S. regulations that specifically stipulates adding vitamin D and zinc to the same product.

6.3 Consumer Sensory Acceptance and Perception

While the fortification of foods with vitamin D and zinc has health benefits, it may also introduce sensory challenges that affect consumer acceptance. Fortification with vitamin D is generally considered to have a minimal impact on taste or appearance due to its low concentration. However, certain forms of vitamin D, especially when used in higher doses or in unstable formulations, can cause off-flavors described as slightly fishy, oxidized, or metallic, particularly in dairy and plant-based beverages [86].

On the other hand, zinc fortification tends to have a more negative effect on sensory properties. Zinc sulfate and zinc gluconate are known to contribute to bitterness, metallic taste, and astringency when added at higher concentrations. Moreover, zinc can interact with other food components like proteins and lipids, potentially leading to undesirable changes in texture, such as grittiness or chalkiness, especially in fortified cereals, yogurts, and beverages [87].

For foods fortified with both vitamin D and zinc, co-fortification generally does not result in a strong synergistic negative sensory effect. Furthermore, the overall sensory profile is dominated by the negative effects of zinc, not vitamin D [77].

Clear labeling indicating vitamin D and zinc enrichment positively influenced consumers' perception of healthiness [88]. For example, beverages fortified with vitamin D that included fortification claims were generally perceived as healthier compared to those without claims. Although minor sensory differences were observed between fortified and non-fortified products, the presence of health-related claims significantly increased consumer acceptance, suggesting that appropriate labelling strategies can mitigate concerns regarding potential flavor changes [88].

7. Future Research Directions and Technical Challenges

Although adding vitamin D and zinc simultaneously to a food can effectively enhance nutritional value, it may have challenges in terms of stability, interactions, bioavailability, flavor and processing compatibility.

One of the major technical challenges is to maintain the stability of vitamin D and zinc. Vitamin D is sensitive to environmental factors such as light exposure, oxygen, and high temperatures leading to rapid degradation and loss of bioactivity during processing and storage [62]. On the other hand, zinc sulfate can act as a pro-oxidant catalyst accelerating the oxidative decomposition of vitamin D when co-present in fortified products [89]. This synergistic degradation complicates efforts to maintain the nutritional integrity and shelf-life of fortified foods.

Vitamin D and zinc have potential physical and chemical incompatibility in foods. Zinc ions can interact with lipid-based carriers of vitamin D, leading to destabilization of emulsified systems and reduced bioavailability of the vitamin. These interactions can cause adverse effects on nutrient efficacy.

Vitamin D and zinc have fundamentally different absorption pathways in the human body, which complicates their simultaneous delivery in a single fortified product. Vitamin D is lipophilic, requiring fat-based absorption mechanisms. While zinc is a hydrophilic mineral absorbed using aqueous pathways. This mismatch demands innovative delivery systems, such as encapsulation techniques, to optimize the bioavailability of both nutrients simultaneously [90].

Zinc is often associated with undesirable metallic and astringent flavors, which can negatively impact consumer acceptance. Although vitamin D itself is flavor-neutral, the presence of zinc may increase the off-flavor perception, particularly in sensitive matrices such as dairy-based beverages [91]. Therefore, sensory masking techniques or protective encapsulation are important considerations during formulation.

To protect vitamin D and zinc during food processing and storage, advanced microencapsulation and dual-encapsulation technologies have been explored. Techniques such as spray drying, freeze drying, and water-in-oil-in-water (W/O/W) double emulsions are commonly used to separately encapsulate the two nutrients, thus minimizing their mutual degradation and improving shelf-life stability [92]. However, these technologies often add complexity and cost to the production process.

8. Conclusions

8.1 Summary of Research and Important Findings

This review discussed the important roles of vitamin D and zinc in human health, the widespread prevalence of their deficiencies, the necessity of fortified foods as a public health intervention, and potential challenges of designing fortified foods with vitamin D and zinc.

Vitamin D has a multifaceted role beyond bone health, influencing immune regulation, metabolic balance, and cancer prevention. Similarly, zinc is essential for immune function, enzymatic activity, tissue repair, and antioxidative defense. They can have synergistic effects on immune function, bone health, and cellular signaling pathways.

Global epidemiological data show high deficiency rates for both nutrients across all age groups, particularly among children, pregnant women, and the elderly. Dietary intake from natural food sources alone is insufficient to meet recommended intakes. Therefore, fortified foods are a necessary way to meet requirements.

Fortification of foods with vitamin D and zinc have potential but there are significant technical challenges. They may have challenges in terms of stability, interactions, bioavailability, flavor and processing compatibility.

8.2 Recommendations for Future Research

Future research should focus on developing advanced encapsulation techniques that effectively stabilize both vitamin D and zinc without compromising bioavailability and sensory qualities. Study on efficient delivery matrices such as nanocarriers,

coacervation systems, or dual-phase emulsions may prove beneficial. Additionally, any new products need to be tested using long-term clinical trials to assess the efficacy, safety, and health outcomes of combined vitamin D and zinc fortified foods. More studies are needed to optimize fortification doses tailored to specific demographic needs and to explore the synergistic mechanisms at the molecular and systemic levels. Integrating consumer-centered sensory research with technological innovation will be important to achieving acceptable and sustainable fortification strategies.

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