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Fortified and functional foods: Trends, innovations, and their public health impact for future nutrient enrichment

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ABSTRACT

Global malnutrition remains a critical public health challenge, necessitating innovative solutions to improve nutrient intake and health outcomes. Functional fortified foods, which incorporate essential vitamins, minerals, and bioactive compounds into commonly consumed foods, have emerged as a promising strategy to combat micronutrient deficiencies. This review addresses the development process, evidence base, and public health relevance of fortified foods and highlights critical challenges such as unequal access, overfortification, and nutrient interactions. Fortified foods have contributed significantly to disease prevention and health improvement over the years. At present, functional foods provide additional benefits in addressing a wide range of diseases. Emerging technologies like genetic biofortification, nanoencapsulation, cold plasma treatment, edible coatings, and 3D food printing have improved nutrient stability, bioavailability, and delivery efficiency. This review concludes by emphasizing the importance of advancing sustainable fortification techniques and personalized nutrition approaches to effectively improve public health outcomes in the coming decades.

1. Introduction

The concept of functional fortified foods has gained significant attention in recent decades, driven by growing consumer awareness of the relationship between diet and health. While fortified foods are traditionally enriched with essential vitamins and minerals to prevent nutrient deficiencies, functional foods provide additional health benefits beyond basic nutrition, often due to the presence of bioactive compounds, probiotics, and antioxidants. Functional fortified foods combine these approaches by incorporating both essential nutrients and bioactive ingredients into commonly consumed foods, enhancing their nutritional value and promoting overall well-being [1,2]. Functional fortified foods fall under functional foods, which enhance specific physiological functions. For example, probiotic-rich yogurt supports gut health and immunity by promoting a balanced microbiome [3]. Additionally, omega-3 fatty acids in fish may help decrease inflammation and promote heart health [4,5]. Furthermore, foods containing fiber, such as oats and flaxseeds, are associated with better digestion and lower cardiovascular disease risk [6]. Moreover, antioxidant-rich foods, such as berries and dark chocolate, protect the cells from oxidative stress, which is linked to aging and a wide range of chronic diseases [7]. What distinguishes functional fortified foods from general functional foods is their targeted nutrient enhancement through fortification, offering additional health benefits. Fortification enhances the nutritional profile of foods by adding essential vitamins, minerals, and bioactive compounds. This process helps prevent deficiencies and supports overall health, particularly in vulnerable populations [8]. Some of the foods commonly fortified are staple foods like flour, milk, and cereals, which are fortified with key nutrients like iron, vitamin D, calcium, and folic acid. Fortification is distinct from biofortification, which raises the nutrient value of crops at the growth stage by genetic modification, selective breeding, or agronomic management [9]. Fortified foods play an especially vital role in

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filling nutritional gaps that lead to more serious health conditions. In general, fortification is meant to increase the nutrient content of widely consumed foods to help prevent conditions associated with deficiency, like iron deficiency anemia, vitamin D deficiency rickets, and neural tube defects due to a lack of folic acid [9,10]. This approach is critical in enhancing public health globally, especially in areas with limited access to a diversified diet-often the case in low- and middle-income regions, hence significantly contributing to lessening malnutrition and its imposing health burdens [11,12]. Food fortification has a long history, emerging as a public health intervention in the early 20th century to combat widespread nutrient deficiencies [13]. Early examples of fortification, in the 1920s, were the iodization of salt to prevent goiter and the fortification with vitamin D of milk to prevent rickets in children, in the 1930s [14,15]. Closer attention to fortified foods, in particular, began to gain ground both during and after World War II, as governments became more interested in improving the nutritional status of the population, establishing a number of widespread programs to add nutrients such as iron, thiamine, and niacin to foods [16]. In Bangladesh, organizations such as the Global Alliance for Improved Nutrition (GAIN), Nutrition International, and the United Nations World Food Programme (WFP) have been instrumental in generating and disseminating data on the effectiveness and implementation of food fortification programs, highlighting their impact on reducing nutritional deficiencies across vulnerable populations [17]. In spite of remarkable progress in the development of fortified and functional foods, there are still knowledge gaps in understanding their long-term health effects, bioavailability, and optimal delivery across diverse populations. Most studies focus on the benefits of individual bioactive compounds, but comprehensive reviews on functional fortified foods are still limited. Additionally, variations in health outcomes across different age groups, regions, and socioeconomic backgrounds require further investigation to maximize their public health impact. This review aims to address these gaps by synthesizing current evidence on the health benefits, safety, and practical applications of functional fortified foods. It uniquely integrates knowledge of both essential nutrient fortification and bioactive compound functionality, highlighting strategies to optimize their effectiveness for broader and more diverse populations. By doing so, this review offers a novel perspective that extends beyond traditional fortification or functional food studies, providing valuable insights for researchers, policymakers, and food industry stakeholders.

2. Historical evolution of fortified foods

2.1. Early developments

Food fortification has a long history, dating back to 400 B.C. when iron was first added to wine. However, during the World Wars, as a strategy to address deficiencies, iodine was added to salt, vitamins A and D were added to margarine, and B vitamins to flour [18]. Food fortification, as a matter of policy to address inadequacies of major micronutrients such as iodine, iron, and vitamin A, has also been implemented in industrialized nations since the 1920s. More recently, parallel efforts within East, Central and South Africa, and Southeast Asia have shown impressive public health benefits via nutrient intake [19]. These fortification efforts, beginning in the 1920s in the United States, first added iodine to prevent goiter, then vitamin D in the 1930s to prevent rickets, followed by fluoride to protect teeth, and most recently folic acid to prevent neural tube defects [20]. These efforts expanded to deal with widespread deficiencies by the middle of the 20th century, leading to the FDA establishing standards, in the 1940s and 1950s for enriching certain staple foods with B vitamins and iron to improve public health [21]. Fortification of blended foods took off after World War II, through the advancement of nutrition science, state-led industrialization to combat protein deficiencies, and the use of U.S. agricultural surplus for humanitarian aid [22]. In a similar way, Nigeria's food fortification initiative, initiated more than 20 years ago, targeted staple foods such as wheat flour, sugar, edible oils, and salt to enhance nutrition. Fortification of wheat flour with iron alone reduced the risk of anemia by 27 %, illustrating the success of the program in countering micronutrient deficiencies [23]. Other key developments in the field of fortified foods are the addition of plant-based proteins to bread, for combating malnutrition, meeting the increased demand for plant-based diets, and improving nutrition with better sourcing and technology [24]. Fortified food innovations include adding plant-based proteins to bread for better nutrition and enhancing baker's yeast with zinc and chromium to fortify baked products and combat deficiencies [25]. Several milestones have marked the development of fortified foods. The mid-20th-century enrichment of flour and bread with B vitamins (niacin, thiamin, and riboflavin) and iron greatly reduced the incidence of pellagra, beriberi, and anemia [24–27]. The post-war period saw the introduction of vitamin C fortification in beverages and the use of fortified infant formula to address infant malnutrition. The introduction of folic acid fortification in the late 1990s was another significant achievement, reducing the incidence of neural tube defects in newborns [28].

2.2. Recent technological advances in fortification

In recent years, new technologies have transformed the whole area of food fortification, brought new insights, and greater scope. These developments expanded the range of nutrients which could be successfully incorporated in foods with improved quality, nutritional value, and acceptance by consumers [29]. Other interesting developments include the application of iron encapsulation technologies using double emulsions and gel beads to improve iron retention and bioavailability in bakery products, dairy, and cereals with minimal organoleptic problems [25,26]. New processing techniques like ultrasound, microwave, and high hydrostatic pressure extract functional elements from food by-products, enhancing the nutritional density by extracting bioactive compounds. These extracts can be used to fortify foods, enhancing nutritional content and antioxidant activity without impacting texture or taste [30]. Combined, these technological advances are significantly enhancing food fortification and making it more efficient and effective in terms of its contribution to improving global nutritional status. As shown in Fig. 1, the evolution of fortification techniques has significantly advanced over time.

Additionally, emerging trends in food fortification reflect shifting consumer preferences for health-promoting attributes beyond basic nutrition. Other functional fortified foods with probiotics, omega-3 fatty acids, and bioactive compounds from plants are meeting the demand for products offering specific health benefits while satisfying hunger. These trends are supported by advances in food science, a better understanding of nutrition, and a focus on preventive healthcare [31]. Some of the notable innovations are the fortification of fermented milk products with different teas, including green, oolong, white, and black teas, to enhance nutritional value, improve the content of bioactive compounds, and increase health benefits [31]. Techniques like spray drying and freeze-drying are part of encapsulation methods to fortify such bioactive components, including stability features that support consumer acceptance of natural ingredients [32]. Fig. 2 shows key milestones in nutritional fortification, from iodized salt in the 1920s to plant-based protein innovations in the 2020s.

3. Scientific evidence

Fortified foods play an important role in improving nutritional deficiencies and public health among populations with limited dietary diversity. They provide the necessary amount of required nutrients, preventing common deficiencies of zinc, iron, and iodine that are widely seen in the Global South. For example, zinc fortification reduces the risk of severe health conditions such as COVID-19 and diarrhea [33]. Programs like fortification of bread with zinc have shown their efficiency in enhancing the absorption of nutrients, supporting immunity, and

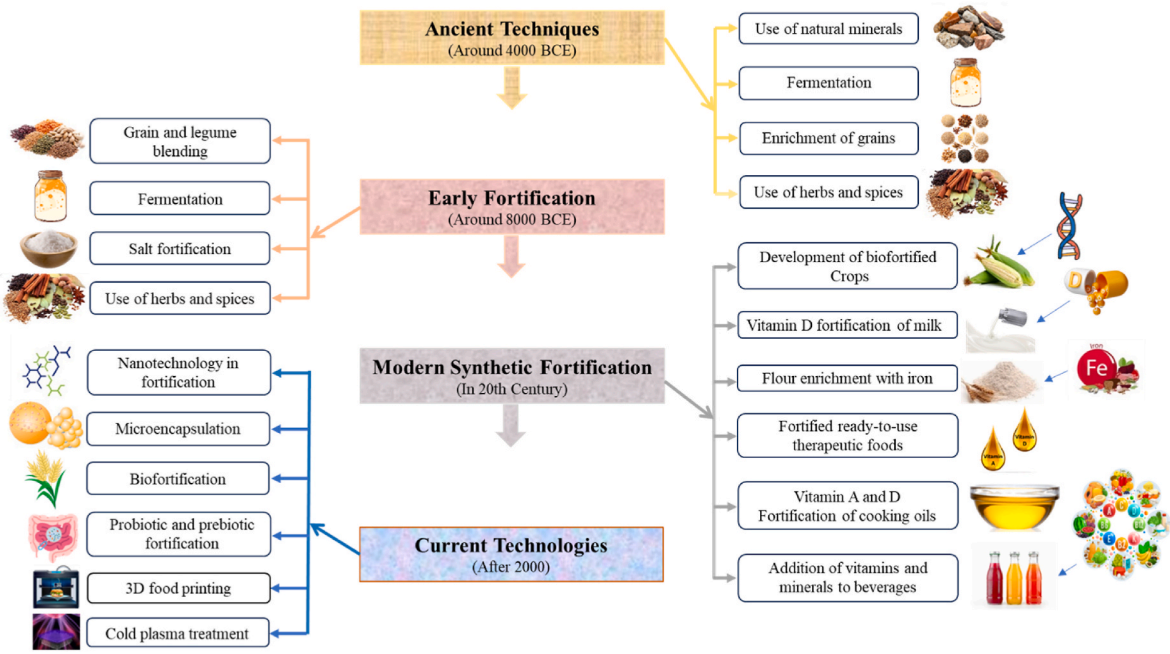

Fig. 1. Evolution of food fortification techniques from ancient to modern times.

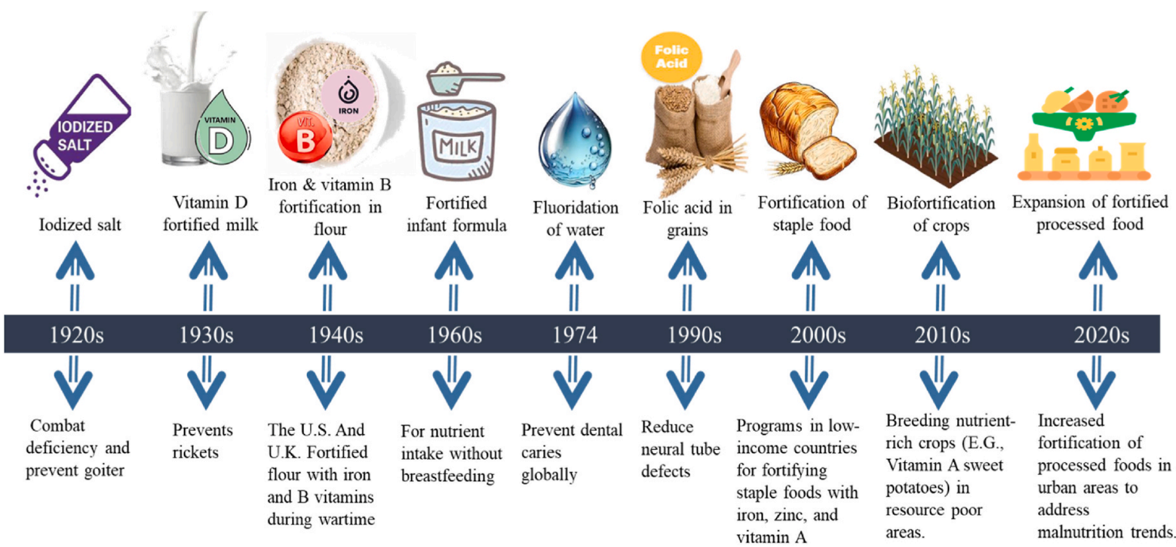

Fig. 2. Timeline of key global milestones in food fortification (1920s–2020s).

improving cognitive development [34]. The biofortification of staple crops is a sustainable way to ensure long-term solutions to fight malnutrition and improve health outcomes [35]. Research has shown that functional food fortification can significantly enhance nutritional and health benefits. For example, fortifying yogurt with quinoa, chickpea, soybean, and rice flours has been found to support the viability of *Lacticaseibacillus rhamnosus* GR-1 at high levels (10^8 CFU/mL), meeting health standards for probiotic efficacy. Among these formulations, rice-fortified yogurt demonstrated the highest consumer acceptance [36]. Nonetheless, public perception challenges regarding genetically modified organisms (GMOs) necessitate transparent communication and culturally sensitive implementation strategies. Nanofortified milk powder demonstrated enhanced calcium absorption and bone strength in osteoporosis-model rats, with significantly improved bioavailability of calcium and vitamin D compared to standard fortification [37]. On the other hand, cold-pressed rapeseed and sunflower oils were nutritionally enhanced by fortification with chia and sesame seeds; however, this treatment had a negative effect on sensory quality after repeated heating [38]. Moreover, the fortification of B vitamins significantly improved the status of B vitamins and cognitive performance among primary school children, showing the potential of fortification to improve health and learning capabilities in children [27]. A review of micronutrient fortification studies found that zinc fortification may help increase serum ferritin levels (an indicator of iron status) but the effects on weight and height remain unclear [39].

3.1. *Comparative analysis of principal fortification techniques and their applications*

In recent years, various food fortification techniques have emerged to address global malnutrition. Direct fortification is one such method where nutrients are added to food during processing, an economical method but, it carries the risk of non-uniform distribution of nutrients [40]. Microencapsulation, by encapsulating nutrients in a protective coating, improves nutrient stability and bioavailability but at a greater cost and complexity [41]. Biofortification, by enhancing the nutrient content of crops through breeding or agricultural practices, offers sustainability but is hampered by implementation challenges and farmer resistance [42]. Extrusion fortification, in which nutrients are added during extrusion, offers even distribution of nutrients, but is expensive and technology-limited [43]. Fermentation fortification, which uses microorganisms to produce bioavailable nutrients, presents a low-cost solution in certain circumstances, but is equipment- and technology demanding [44]. Additionally, cold plasma [45], edible coatings [46], nanoencapsulation [48], and 3D food printing [49,50] offer novel fortification options with benefits like targeted delivery and quality retention. However, they face challenges such as high cost, technical complexity, and limited scalability. Table 1 summarizes these techniques with their respective advantages and limitations.

Food fortification is the enhancement of nutrient delivery through multiple mechanisms with differing advantages and limitations. Fortification and microencapsulation provide enhanced stability in nutrients, while biofortification and fermentation provide long-term benefits. Fig. 3 schematically shows different nutrient delivery mechanisms in fortified foods, with mechanisms enhancing absorption and making up for deficiencies. Awareness of these methods optimizes fortification programs to be more effective in the battle against malnutrition on a mass scale.

3.2. *Evidence from human trials on fortified foods*

Human studies around the world have shown impressive impacts of food fortification on micronutrient deficiencies. In Rwanda, staple foods fortified during the program in 2019, with vitamin A, iron, and zinc, recorded improved nutrient intake among vulnerable groups. In Indonesia, vitamin A added to cooking oil accounted for 26 % of daily needs of the nutrient among children and thus reduced the deficiency. For instance, Costa Rica's iron fortification program resulted in a significant decrease in anemia, while the Philippines found the fortification of powdered milk with iron was a cost-effective way to address the problem of iron deficiency in children [51]. Consumed as a staple food, rice presents a unique opportunity to address micronutrient deficiencies, particularly iron and zinc, through effective fortification strategies [52]. In India, iron-fortified rice through the Public Distribution System had high acceptability, resulting in decreased anemia outcomes with no adverse effects [53]. Fortified food made of ultra-processed foods with the fortification increased intake in Brazil; this has improved the risk of anemia among children from families of low income, though with a decline in the overall diet quality [54]. The effectiveness of food fortification programs in improving micronutrient deficiencies and overall public health outcomes, particularly in vulnerable populations, has been well-documented. Moreover, several large-scale experiments have provided valuable insight into the efficacy of fortified foods under real-world conditions. A randomized controlled trial in Rwanda and Burkina Faso found that energy–protein supplements fortified and provided to pregnant and lactating women significantly enhanced maternal iron status and reduced low birth weight by 19 % [55]. The study in Lebanon demonstrated that vitamin D-fortified bread was well accepted, increased intake among poor households, and had no adverse effect on sensory quality [56]. Overall, these findings put food fortification at the center as an effective and viable intervention to offer micronutrient relief to a large cross-section of populations. However, long-term follow-up studies evaluating extended effect, adherence, and biochemical outcomes have not yet been conducted in several low- and middle-income nations. Table 2 summarizes major research studies that assess the efficacy of fortified foods in addressing nutrient deficiencies and improving health outcomes.

4. Health benefit of fortified food

4.1. *Micronutrient enhancement and associated health benefits of fortified foods*

The addition of certain vitamins and minerals to foods, such as iron-enriched rice and noodles, has been shown to raise iron levels and reduce anemia. For example, adding *Lentinus edodes* mushroom powder to noodles not only increases protein content but also enhances iron bioavailability, supporting ferritin synthesis and preventing iron deficiency [53]. Yogurt containing microencapsulated iron is another example aimed at enhancing iron availability with a minimum of undesirable sensory effects [71]. Iron-fortified lentils (IFLs) have been evidenced to impact the iron status of adolescent girls positively, slowing the decline in levels of serum ferritin (sFer), hence reducing the risk of iron insufficiency in comparison with those with a normal intake of iron [72]. Vitamin D-enhanced bread, one of the staple foods in everyday consumption, prevents vitamin D deficiency, which is important for maintaining bone health [73]. Besides, calcium-fortified fresh milk, with casein phosphopeptides and vitamin D, has been able to enhance the bone mineral content and density in the lumbar spine and femur and thus could be used as a possible therapeutic agent in postmenopausal osteoporosis [74]. Fortification of wheat flour with zinc is a very effective way to address zinc deficiency, as the fermentation process increases zinc bioavailability due to a breakdown in phytate, an inhibitor of zinc absorption in the gastrointestinal tract [75]. Fortified

Table 1
Summary of key food fortification techniques, advantages, and limitations.

Fortification technique	Description	Advantages	Limitations	References
Biofortification	Enhancing nutrients in crops through breeding or practices	Sustainable, no need for post-harvest fortification	Slow implementation, resistance from farmers	[42]
Direct fortification	Adding nutrients directly during processing	Simple, cost-effective, easy to implement	Uneven nutrient distribution if not done carefully	[40]
Microencapsulation	Nutrients encased in a protective coating	Enhances stability and bioavailability	Higher production costs, complexity	[41,47]
Extrusion fortification	Nutrients added during the extrusion process	Even nutrient distribution, can fortify a variety of products	Expensive, limited by available technologies	[43]
Fermentation fortification	Using microorganisms to produce nutrients	Produces bioavailable nutrients, cost-effective in some contexts	Requires specific equipment and expertise	[44]
Cold plasma treatment	Non-thermal processing to enhance nutrient uptake or surface fortification	Preserves food quality; environmentally friendly	Still experimental; equipment-intensive	[45]
Edible coatings with micronutrients	Thin nutrient-enriched films applied to food surfaces	Maintains appearance; easy integration in fruits, snacks	Stability and uniformity issues; limited nutrient types	[46]
Nanoencapsulation	Nutrients encapsulated at nanoscale for targeted delivery	Improves bioavailability; protects sensitive nutrients	Regulatory uncertainty; long-term safety data emerging	[48]
3D food printing	Customized, layer-by-layer printing of food with nutrient cartridges	Enables personalized nutrition; precision delivery	High cost; not yet scalable	[49,50]

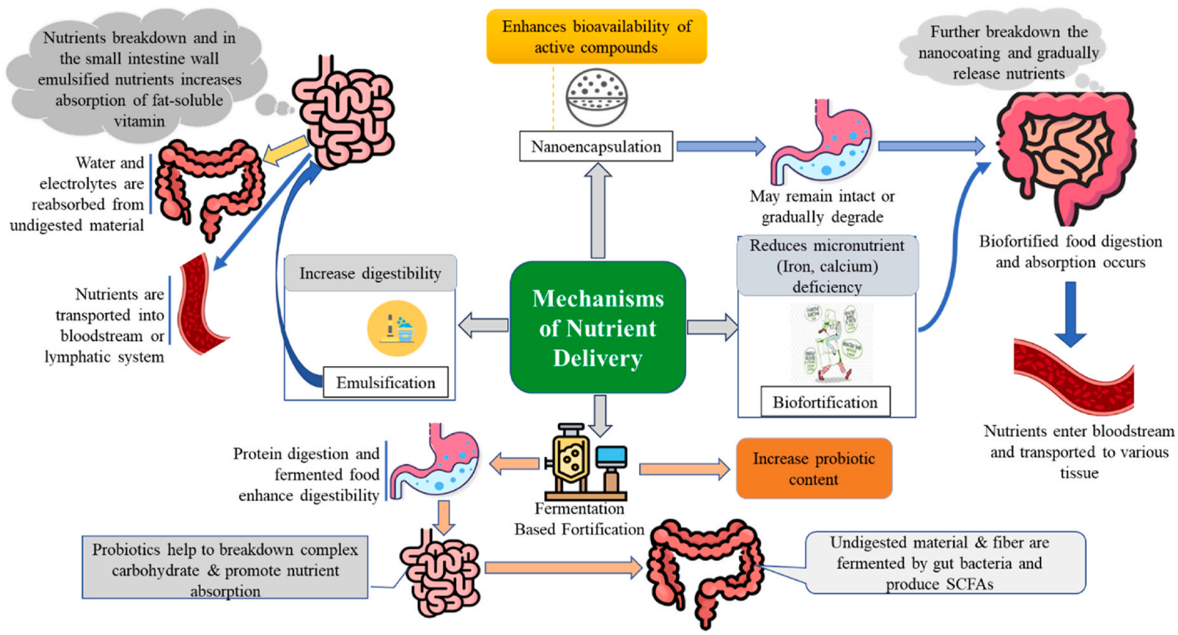

Fig. 3. Mechanisms of nutrient delivery in fortified foods.

foods offer great potential for improving micronutrient deficiencies, immune response, cognitive development, and good health. For example, calcium-fortified water and wheat increase calcium intake which is important for immune activity, while iodine-fortified lettuce contributes to better body homeostasis and increased levels of vitamin D, thereby increasing the efficiency of the immune system [76]. Yogurt fortified with *Lactobacillus bulgaricus* and *Streptococcus thermophilus* has been shown to enhance respiratory immunity, potentially offering better protection against respiratory infections compared to ordinary yogurt [77]. Vitamin B12 supplementation through yogurt is more convenient and can help to overcome the deficiency of B12, which impairs immune function and heightens infection susceptibility. Such fortification raises plasma B12 levels, thereby sustaining immune function, particularly in those who are deficient [78]. Vitamin B12 also plays an essential role in cognitive health. Cereals fortified with B12 have been reported to prevent loss of memory, cognitive impairment, and megaloblastic anemia effectively [79]. In addition, consumption of micronutrient-fortified foods has shown enhancement in children's performance through improved cognitive function [80]. These functional foods, rich in essential nutrients, help reduce the risk of chronic diseases like diabetes, heart disease, and cancer, and also maintain immune function, tissue repair, and overall health [81]. Besides, the consumption of vegetable oil fortified with vitamin A significantly increases the intake of vitamin A, which is essential for maintaining general health [82]. Table 3 lists some common nutrients added to foods in a fortification program along with their health benefits.

4.2. Health impacts of fortified foods on vulnerable populations

Specifically, the fortification of foods with essential vitamins and minerals can go a long way in improving the nutritional health of vulnerable populations in poor countries. The fortification of fruits like strawberries with key micronutrients like Zn and folate contributes to improved nutrient intake in mothers and children. Zinc plays an important role in the activity of enzymes from metabolic pathways and cellular respiration, while folic acid is important in the process of new tissue development, erythropoiesis, and protein synthesis. Shortages in some micronutrients can lead to a significant health burdens such as megaloblastic anemia among pregnant women and stunted growth in children [94]. Additionally, fortification of corn soy blend with whey or skim milk powder improves its protein value and is thus useful for populations suffering from undernourishment, such as children and individuals with HIV/AIDS. Addition of milk proteins also improves flavor and acceptance [95]. Cereal-based bread fortified with prebiotic helps the elderly people suffering from gastrointestinal disorders and thus promotes colonic health and overall well-being [96]. Vitamin powders are also convenient vehicles to enhance micronutrient intake by undernourished children in order to promote growth and immune function [97]. In addition, iron and calcium were considered essential to produce hemoglobin and in bone health, respectively. On one hand, fortified rice beverages enhance the bio accessibility and absorption of these minerals, leading to improved health outcomes [98]. On the contrary, a diet comprising non-fortified foods may cause nutrient deficiencies that can lead to a host of health complications, especially in populations for whom these foods are a main diet [90]. Ultra-processed foods are also associated with obesity, metabolic diseases, and adverse health outcomes [99]. While this issue is critical to public health, it may be more relevant in broader discussions of diet-related diseases than specifically in relation to vulnerable populations. Moreover, the consumption of high amounts of chemical-laden foods with no fortification enhances risks of mortality, mental disorders, and chronic diseases, specifically cardiometabolic diseases [100]. Furthermore, negative cardiometabolic effects of diets can be produced from non-fortified ultra-processed foods like sweetened soymilk that inhibit positive effects of plant-based diets [101].

5. Adaption and barriers to fortified food

5.1. Consumer awareness, perceptions, and barriers

Consumer preference and awareness are the major driving forces for the adoption of fortified foods. It has attracted an increasing health-conscious market, which has demanded more nutritionally enhanced food products. Sensitization through public campaigns, informative labeling, and certification schemes like health claims on packaging has been crucial to increase awareness about the benefits accruing from fortification. On the other hand, studies demonstrate that foods with visible health claims are usually sold in higher quantities, especially for urban and health-conscious demographic groups [102,103]. However, a wide gap still persists in rural areas and lower-income groups of people

Table 2
Summary of scientific evidence on fortified food efficacy.

Study design	Sample size	Key findings	Reference
Randomized controlled trial	FA fortification among countries that fortify (n = 71)	Mandatory folic acid fortification programs have reduced neural tube defects by up to 78 % and increased blood folate levels.	[57]
Randomized controlled trial	1897 pregnant women	Improved infant linear growth.	[58]
Microsimulation model-based study	Simulated cohorts of the French population aged 60+ (3 age groups: 60–69, 70–79, >80 years, both genders)	Prevented 64,932 fractures, 32,569 QALYs gained.	[59]
Top-down cost-of-illness study	Data from 2010 to 2019 (Brazil)	Fortification prevented 3499 cases, saved R $8.9M, and reduced prevalence by 30 %.	[60]
Double-blind placebo-controlled trial	300 adolescents	Zinc-fortified wheat improved immune response and reduced infection rates.	[61]
Dietary modeling study	Populations in Bangladesh, Guatemala, and Uganda	Calcium-fortified water/flour with FBRs met calcium targets for vulnerable groups.	[62]
Cross-sectional analysis	2430 elderly participants (aged 60+)	Higher omega-3 intake correlated with better cognitive function.	[63]
Pre–post evaluation	Baseline: 324 lactating mothers, 318 infants, 469 children; endline: 349 lactating mothers, 335 infants, 477 children	Fortified oil improved vitamin A intake and retinol status in Indonesian women and children.	[64]
Follow-up of RCTs	Data from 4 trials (India and Tanzania)	Vitamin B12 supplementation during early life may enhance neurodevelopment and growth outcomes.	[65]
A systematic review	A total 64 studies (439,649 women) contributed to meta-analyses	Micronutrient supplementation during pregnancy in low- and middle-income countries improves maternal and child health outcomes.	[66]
Cohort study	137 pregnant women	Prepregnancy iodine supplement use linked to improved thyroid function during pregnancy and postpartum.	[67]
Randomized, placebo-controlled	90 pregnant women	Iodine supplementation (225 μg/day) improved urinary iodine-to-creatinine ratio and reduced thyroglobulin levels during pregnancy without adverse effects.	[68]
Controlled net house experiment	Six rice varieties treated with EDTA-Fe	Palman579 and HBC19 exhibited the highest iron content in grains. Increased antioxidative metabolites and enzyme activities reduced ROS damage, enhancing tolerance to high iron levels.	[69]
Mixed-method, sequential exploratory study	Six districts from six states; PDS officials, FPS dealers, and ≥7 households per FPS	Continuous fortified rice supply through PDS; good acceptability, compliance, and no adverse effects; feasible for anemia impact studies.	[70]

Table 3
Common nutrients used in food fortification and their health benefits.

Nutrient	Purpose/health benefit	Commonly fortified foods	Reference
Iron	Supports oxygen transport and energy production; prevents anemia	Cereals, flour, rice, infant formula	[83]
Vitamin A	Essential for vision, immune function, and cell growth	Milk, margarine, sugar, oils	[84]
Vitamin D	Supports calcium absorption and bone health	Milk, orange juice, breakfast cereals	[85]
Folic Acid	Reduces risk of neural tube defects in newborns	Flour, rice, pasta, breakfast cereals	[9]
Calcium	Builds and maintains bone structure and function	Orange juice, breakfast cereals, plant-based milks	[9,86]
Iodine	Essential for thyroid function and cognitive development	Salt, dairy products, bread	[20,33]
Zinc	Supports immune health and wound healing	Breakfast cereals, infant formula, snack foods	[33]
Vitamin B12	Necessary for nerve function and red blood cell formation	Breakfast cereals, soy milk, nutritional yeast	[79,87]
Niacin	Helps convert food into energy and maintains healthy skin	Bread, rice, pasta, breakfast cereals	[88]
Omega-3 Fatty Acids	Supports heart and brain health	Milk, eggs, some yogurts, infant formula	[4,63]
Folate	Essential for cell division and DNA synthesis	Breakfast cereals, pasta, rice	[89,90]
Riboflavin	Supports energy production and cell function	Bread, pasta, milk, cereals	[91]
Thiamine	Assists in energy metabolism and nerve function	Bread, pasta, cereals	[92]
Vitamin E	Antioxidant that protects cells from damage	Breakfast cereals, plant-based oils	[93]
Vitamin C	Supports immune function and iron absorption	Fruit juices, cereals, fruit-flavored snacks	[83]

where affordability and a lack of awareness are still major drawbacks for the wide dissemination of these products. Fortification programs face several barriers such as lack of awareness, limited access to fortified foods, and high costs. Research indicates that targeted outreach efforts, such as educational campaigns, can increase consumer awareness and demand [104]. Additionally, improving access through distribution channels and reducing prices for vulnerable populations has proven effective in increasing adoption [105,106]. Consumer attitudes play a significant role in the adoption of fortified foods, influenced by health consciousness, safety, affordability, and cultural attitudes. Favorable attitudes encourage adoption, but barriers like misinformation, cost, and resistance to diet change can discourage general acceptance. As the factors show in Table 4, these establish consumer behavior and necessitate guided education, transparent labeling, and price reduction interventions to facilitate acceptance and access of fortified foods.

Equity in access is a recurring weakness of current fortification approaches. Urban and wealthier groups have higher chances of benefiting from fortified foods due to higher awareness and affordability, while rural and vulnerable groups tend to be left behind [107]. Distribution

Table 4
Factors influencing consumer perception and adoption of fortified foods.

Factor category	Motivating factor	Impact on consumer behavior	Barrier to adoption	References
Health and safety	Awareness of health benefits	Drives consumers to try fortified foods	Lack of awareness leads to reluctance	[109,110]
	Perceived safety of ingredients	Promotes acceptance and trust in products	Concerns about safety can prevent adoption	[104]
Knowledge and education	Knowledge of nutrition	Encourages informed choices and adoption	Limited knowledge causes hesitation	[111]
	Education on health risks	Supports proactive behavior for better health	Misinformation creates distrust	[112]
Cultural and social influence	Peer influence	Positive reinforcement from social circles	Cultural norms or family habits may limit adoption	[105]
	Family practices	Established habits lead to consistent consumption	Family resistance limits dietary changes	[112,113]
Economic factors	Product affordability	Drives consumption in cost-sensitive groups	High-cost limits access for low-income groups	[40]
	Value for money	Increases purchase likelihood if perceived as beneficial	Perceived lack of value reduces interest	[106]
Product characteristics	Sensory appeal (taste, texture)	Enhances consumer satisfaction and repeated use	Poor sensory qualities deter purchase	[114,115]
	Convenient packaging and availability	Easier to purchase and integrate into daily routine	Inconvenience limits usage	[40,112]

problems, higher product prices, and low availability of locally adapted fortified products are a few among many reasons for this inequity. Studies from Bangladesh [82], Nigeria [23], and Ethiopia [90] suggest that subsidized distribution channels, targeted social marketing, and public-private partnerships can significantly improve access and uptake of fortified foods among low-income populations [108]. Addressing such concerns is essential to the achievement of fortification programs.

5.2. Impact of cultural and regional factors on the acceptance of fortified foods

There are many cultural and regional reasons for the acceptance or rejection of fortified foods. Iron-fortified rice has been tried in regions like South Asia where rice is the staple to combat widespread anemia [116]. In the West, the emphasis on fortifying dairy products and cereals was based on a perceived common deficiency in vitamin D and calcium [117]. Taste preferences, traditional dietary habits, and religious considerations have a major influence on the design and implementation of fortification programs and need to be carefully considered in order to gain acceptance. Regional case studies, such as the introduction of biofortified maize in sub-Saharan Africa, show that adapting fortification strategies to local food consumption patterns and nutritional needs enhances both acceptance and effectiveness [118]. The key to maximizing the impact of fortification programs is to ensure that they fit within the cultural norms and dietary habits, thereby meeting the nutritional needs of diverse populations.

5.3. Economic feasibility and cost-effectiveness analyses of fortification programs

Economics play a crucial role in the sustainability of fortified foods in public health programs. Food fortification is cheaper and scalable than supplementation programs since it adds nutrients to foods that individuals would otherwise be consuming, reducing distribution and compliance issues that accompany single supplements. For example, the World Health Organization (WHO) has estimated that iodizing salt costs just 0.05 US dollars per head annually while, for the improved health payoff, it represents an exceptionally cost-effective intervention, being that it reduces iodine deficiency disorders [119]. Overheads can also be lower by adding fortification onto the existing food production line because often, this means there are no large infrastructural building requirements in many such operations [120]. However, the cost-effectiveness of fortification does not come without any pitfalls. Matters like enforcing the application of fortification policies among industries, proper monitoring systems for this very purpose, and how to deal with any development of market distortions-developments leading to inflation in prices of fortified goods-is what needs to be developed. The overall economic effect, nevertheless, remains positive if interpreted against the backdrop of reducing costs related to serious and crippling health disorders occurring in a micronutrient-lacking diet.

5.4. Strategies to ensure the long-term sustainability of food fortification initiatives

The economic dimension of the effects of fortified foods makes the food a feasible public health intervention. Fortification tends to be one of those cost-effective and scalable strategies against the rest, namely supplementation programs. The addition of fortification to existing food production systems also has lower overhead costs, given it can be included as part of the regular processing package with little need for major additional infrastructure [120]. In terms of the cost-effectiveness of the process, however, fortification has challenges in its pathway that must be overcome; for instance, compliance of industries producing mass food items with the stipulated standards for fortification, proper monitoring mechanisms within an economy, and also avoiding possible market distortions (such as significant price increases) of fortified goods. These, however, are outweighed by a general economic positive effect regarding fortification, especially within the scope of preventing extremely costly health problems due to micronutrient deficiencies. On the economic side, market fluctuations in raw material costs can impact the affordability of fortified products for both manufacturers and consumers [102]. Innovations like biofortification, which integrates fortification into agricultural practices (e.g., genetically engineered crops), present a promising sustainable alternative [59,68,69].

6. Regulatory and safety considerations

6.1. Global regulatory frameworks and standards governing food fortification

Food fortification practices are regulated globally with respect to safety, efficacy, and public health benefits. The WHO, the U.S. Food and Drug Administration (FDA), and the European Food Safety Authority (EFSA) are examples of organizations that provide a framework for fortification programs. The WHO outlines fortification as an essential strategy to combat micronutrient deficiencies, with specific recommendations on fortified foods and nutrient levels tailored to population needs [21]. Despite international standards, their implementation and regulation vary across countries. Low- and middle-income nations struggle to establish and enforce mandatory fortification legislation. Inadequate lab facilities, weak monitoring, and poor data enforcement act as impediments to effective fortification schemes [121]. Harmonization of international standards is also problematic, especially for fortified products imported across borders. Regulatory capacity building and cross-country coordination should be top priority in future endeavors to improve the governance of fortification across the globe. The

FDA has mandated the levels of fortification to meet Recommended Dietary Allowance (RDA), ensuring that fortified foods provide useful amounts but not at harmful levels [122]. Similarly, EFSA assesses fortification practices for nutrient safety, bioavailability, and compliance with European Union (EU) food law, emphasizing evidence-based approaches [123]. Table 5 presents some of the regulatory guidelines on food fortification in different regions; there are differences in standards and implementation practices.

6.2. Potential risks associated with fortification and monitoring mechanisms to ensure safety

6.2.1. Potential risks

Although fortification has great health benefits, excessive or improper fortification carries several risks, including nutrient toxicity and adverse nutrient-nutrient interactions. For example, excessive fortification with iron can cause iron overload disorders, such as hemochromatosis, especially in those with genetic predisposition to the condition [129]. Highly variable intakes of vitamin A through fortification can lead to symptoms of toxicity, which include liver damage and teratogenic effects, raising concerns about threshold levels for nutrients [130]. Besides, nutrient-nutrient interactions, such as the inhibition of iron absorption by calcium, illustrate the complexity of fortification safety and highlight the need for careful formulation to avoid unintended adverse effects [131]. Excessive fortification, especially without regulatory control, may lead to unjustified nutrient over intake by individuals who are already meeting their requirements through diet. For example, studies conducted in developed nations have shown increased risk of vitamin A toxicity and iron overload as a result of consuming multi-fortified foods [132]. Moreover, additive exposure from having multiple sources of fortified foods is seldom addressed in dietetic analysis [133]. Therefore, there is a need to closely monitor the level of nutrients among the population and follow up on upper safe intake limits to prevent any unwanted health problems.

6.2.2. Monitoring practices

Monitoring and evaluation are central to the safety and success of the fortification programs. Surveillance systems track nutrient intakes at the population level for the prevention of deficiencies or excesses and assure compliance with the WHO's global monitoring of fortification guidelines [134]. Bioavailability studies and biomarkers, such as serum ferritin for iron, are used routinely to assess the health effects of consuming fortified foods [135]. Most national and regional regulatory agencies also require periodic assessment to review the legislative framework and targeted food vehicles for public education to ensure the level of safe consumption to avoid risks of over-fortification.

7. Innovations and future perspectives in fortified foods

7.1. Emerging bioactive compounds and advanced delivery systems in functional food innovation

Recent advances in food fortification technologies have greatly improved the opportunity for improving micronutrient deficiencies, enhancing the bioavailability and stability of the essential nutrients. Among novel encapsulation techniques applied in iron fortification, double emulsions with more than 88 % encapsulation efficiency and, as well as gel beads designed to enhance the release of iron under gastric conditions greatly improve the bioavailability of iron in staple foods such as cereals and bakery products [136]. Although nanotechnology and encapsulation have improved the delivery of nutrients, there are few practical applications to date that must be explored. For example, nano-iron particles added to milk powder significantly increased hemoglobin and iron absorption in preclinical studies [137]. Similarly, vitamin B12 encapsulated within cereals enhanced serum B12 concentrations in older adults without affecting taste [138]. These innovations achieve targeted delivery with increased bioavailability but require clinical trials and long-term safety testing in order to guarantee their impact on public health at scale. On the other hand, microencapsulation techniques have been adopted for enhancing stability and controlled release of vitamin B12; hence, encapsulated and free forms were incorporated into staple foods as an effective way of addressing deficiency diseases [87]. Similarly, nano formulations have been developed to enhance delivery, bioavailability, and stability of micronutrients and bioactive compounds, overcoming challenges such as nutrient degradation and unpleasant sensory attributes [139]. Nanotechnology has also transformed food fortification through the use of nanoparticles, nano capsules, and nano emulsions that enhance encapsulation, delivery, and protection of bioactive compounds, increasing nutrient bioavailability and enhancing the nutritional value of processed foods altogether [140]. Emerging nanocarriers, such as lipid-based nanoemulsions, demonstrate superior stability and enable the controlled release of micronutrients, offering transformative potential for advancing fortified food delivery systems. Meanwhile, green non-thermal technologies like UV light, high-pressure processing, pulsed electric fields, ultrasound, and cold plasma are being applied to improve phytochemical extraction and bioaccessibility while preserving the nutritional and sensory qualities of fruit and vegetable beverages [141].

Table 5
Regulatory guidelines for food fortification across different countries.

Region/Country	Nutrient(s) fortified	Regulatory body	Guidelines/Standards	Key features	Reference
United States	Iodine, iron, folic acid	FDA, USDA	Mandatory fortification of certain foods (e.g., flour)	Emphasis on preventing deficiencies, safety monitoring	[122]
Canada	Iron, folic acid, vitamin D	Health Canada	Voluntary and mandatory fortification of grains	Fortification levels regulated, public health focus	[89]
European Union	Iodine, folic acid, vitamin D	European Food Safety Authority (EFSA)	Compulsory for certain food categories in some countries	Variability in regulations among member states	[123]
Australia/New Zealand	Iodine, folate	Food Standards Australia New Zealand (FSANZ)	Mandatory fortification of bread with folate	Focus on public health, health benefits assessment	[124]
India	Iron, vitamin A, iodine	Food Safety and Standards Authority of India (FSSAI)	Enforced fortification of wheat flour and salt	Specific guidelines for rural and urban populations	[125]
South Africa	Vitamin A, iron	Department of Health	Mandatory fortification of maize meal and wheat flour	Targets specific deficiencies prevalent in the region	[126]
Brazil	Iron, folic acid	Brazilian Health Regulatory Agency (ANVISA)	Compulsory fortification of flour and corn products	Public health focus, tailored to local needs	[127]
WHO recommendations	Various (e.g., iron, vitamin A, iodine)	World Health Organization	Guidelines for food fortification strategies	Emphasizes evidence-based practices for global health	[132]
Bangladesh	Iodine, iron	Bangladesh Food Safety Authority	Mandatory fortification of salt with iodine and edible oil fortification with Vit-A	Targeted at reducing iodine deficiency disorders	[17]
China	Iodine, iron	National Health Commission	Mandatory fortification of salt with iodine	Strong government oversight and health policy focus	[128]

The fortified and functional foods contain new bioactive compounds and innovative nutrients to meet special health needs. As an example, bamboo shoots are a rich source of minerals, vitamins, dietary fiber, phytosterols, and phenols, being very useful in the development of new healthy food products with new nutrients and bioactive compounds [142]. Other bioactive compounds, such as peptides, phytosterols, fibers, and fatty acids, have also been incorporated into new food formulations to enhance nutritional value and provide more health benefits. These additions also respond to the demand of consumers for natural, nutritious products using cost-effective sources, such as food industry waste and by-products [143]. The addition of carotenoids, phytosterols, polyphenols, and Omega-3 fatty acids as bioactive ingredients in nutraceuticals for health benefits in fortified foods mainly prevents and controls the incidences of chronic diseases [144]. Recent trends also include personalized fortified food products tailored for specific populations, such as diabetics, seniors, and post-COVID-19 patients, meeting diverse nutritional and health requirements [145]. Macroalgae, commonly known as seaweeds, are nutrient-enriched and contain high levels of bioactive compounds and therefore are the most suitable candidate for food fortification. They have a very high protein content (6–30 g/100 g DW), low in lipids, and a high antioxidant content, factors that all boost the nutritional values and health impact of fortified food [146]. Innovations are also emerging in the form of fortified functional and medicinal beverages enriched with botanical ingredients, combining both exotic and natural components to appeal to health-conscious consumers [147]. The integration of bioactive compounds such as vitamins, minerals, organic acids, dietary fiber, phenolic compounds, essential amino acids, and antioxidants into fortified foods not only helps address micronutrient deficiencies but also improves overall nutritional quality [148]. Biofortification, led by genetic and agricultural innovation, has become an important intervention to tackle malnutrition in many parts of the world. The future trends in addressing micronutrient deficiencies will, therefore, involve developing climate-resilient and nutrient-rich crops. Besides, the use of digital technologies like machine learning will be important in enhancing breeding strategies towards improved nutrient profiles in crops [149].

7.2. Prospects in personalized nutrition, digital technologies, and biofortification approaches

Future trends in biofortification will involve greater collaboration among plant breeders, molecular scientists, and nutrition experts, with increased funding from global organizations. With new genetic engineering methods and advances in agronomic practices, such as nanofertilizers and mechanized applications, the enhancement of micronutrient content and bioavailability in crops will help in solving global food and nutrition security challenges [150,151]. In the near future, CRISPR-Cas9 technology will play a major role in biofortification through the precise modification of genomes with the aim of improving crop nutrition and alleviating deficiencies in resource-poor environments [152]. In addition, the incorporation of chloroplast genome engineering, synthetic biology, and nanoparticle-mediated transformation will improve metabolites, restore lost nutrients, and introduce novel phytonutrients contributing to enhancing the nutritional quality of staple food crops [153]. Shifting consumer demands are driving the future of enhanced foods, as more demand is being generated for products to improve health and well-being. Some of the most important innovations in these categories are creating personalized nutrition options, which resonate with personalized health needs, and improving the quality of taste enhancers so that health benefit is not sacrificed while quality is preserved. The food industry is doing everything it can to balance these aspects, developing tailored foods that are not only nutritionally sound but also tasty enough for consumers [154]. Acceptance of the fortified products is on the rise, especially in the post-COVID-19, due to increased awareness of nutritional benefits combined with sensory properties. The higher acceptability is still hindered by cost and faith in the product claims, and all these have to be taken care of through transparency and consumer education for any further growth to occur [155,156]. In fact, the latest thinking in consumer preference involves segmentation-based marketing, product, and packaging strategies targeting consumer preference for different audiences so that this fortified food becomes affordable, available, and appealing. The discussed approach supports public health and further allows consumers to make choices in a nutritionally informed manner. In addition, the increasing preferences for health, sustainability, and reduction of waste have been driving cereal-based products fortification. Such initiatives have been in line with global actions, such as those from the United Nations' Agenda 2030, focusing on enhancing well-being and nutritional quality [157]. Furthermore, sustainable fortification strategies that utilize local, nutrient-rich ingredients and minimize food waste are aligned with international nutrition and sustainability goals [158].

8. Identification of research gaps pertaining to effectiveness, accessibility, and sustainability of fortification programs

Despite the tremendous progress in food fortification, there are still some knowledge gaps regarding its wider effects and potential. For instance, the health impact of the long-term consumption of nutrient-fortified foods, particularly due to the cumulative interactions, is still underexplored, especially regarding overconsumption risks in populations on diverse diets [159]. Moreover, the nutrient bioavailability in fortified foods under varying conditions, such as diet and gut health or microbiome diversity, needs further investigation [160]. Another important area of research is the fortification of non-traditional food matrices, such as plant-based and ultra-processed foods, where nutrient stability and retention studies are still ongoing [161]. The effects of fortification on sensory attributes and consumer acceptance in diverse cultural contexts also require more comprehensive studies to ensure wider adoption. In addition, cost-effectiveness studies of the fortification programs in countries of low-and middle income, considering logistics, regulatory frameworks, and consumer access to fortified products, have not been conducted [162]. There is also a serious lack of studies that take into account the potential negative implications of fortifying staple foods, such as replacing the natural dietary sources of nutrients [163]. Finally, investigation of personalized fortification strategies, including the use of emerging technologies such as nutrigenomics and precision nutrition, opens the door for targeted effective interventions [164]. Future research will need to focus on precision fortification strategies, using new technologies such as nutrigenomics and metabolomics, which consider the nutritional needs at an individual level. The role of fortification in addressing the dual burdens of malnutrition, undernutrition and obesity-also needs to be investigated, especially in low- and middle-income countries where both forms of malnutrition coexist [162]. Moreover, there is a need for more research on sustainable fortification approaches, such as biofortification and the use of eco-friendly delivery systems, in order to meet global sustainability goals. Other areas that require further studies are the socio-economic constraints to the adoption of fortified foods, especially among marginalized communities, and culturally adapted interventions that improve the acceptability and effectiveness of the fortification programs [165]. Furthermore, it is needed to establish validated measures and longitudinal data sets that quantify the long-term public health value and cost-effectiveness of mass fortification interventions, such as biofortification and nano-based ones. The integration of fortification programs with broader public health initiatives, such as nutrition education and disease prevention campaigns, could maximize their impact and sustainability [117,118,120]. Moreover, research into scalable and cost-effective fortification technologies, including nanotechnology-based nutrient carriers and microencapsulation, could enhance nutrient stability and bioavailability in diverse food matrices [102,148,166].

9. Conclusion

Fortified foods are significant contributors to nutritional deficiency prevention, immune function, cognitive performance, and risk reduction for chronic disease. Functional fortified foods go a step further. They incorporate bioactive components that provide benefits for general health and disease prevention. New technologies in fortification, ingredient mixing, and nutrient delivery systems have significantly improved the effectiveness and scope of such interventions. However, their success depends on integrating culturally adapted strategies, robust regulatory oversight and innovative delivery mechanisms. To be most impactful, strategic action is required across sectors. Policymakers should prioritize regulatory framework enhancement, quality control, and equitable access promotion, especially in low- and middle-income countries. The food industry should invest in sustainable, consumer-acceptable innovations such as nanoencapsulation, biofortification, and personalized nutrition and enhance affordability, label clarity, and sensory appeal. Researchers should prioritize long-term studies on nutrient interactions, health outcomes, and culturally adapted fortification approaches. Further investigation into personalized nutrition and nutrigenomics will also enable the development of targeted, effective interventions. Fortified and functional foods can take a prominent position in advancing global nutrition and in reaching public health and sustainability goals through concerted efforts, scientific innovation, and inclusive strategies.

CRediT authorship contribution statement

Md. Sakhawot Hossain: Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization, Formal analysis, Resources. **Md Abdul Wazed:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Suvasish Das Shuvo:** Writing – review & editing, Validation, Conceptualization. **Zakia Sultana:** Writing – review & editing, Visualization, Resources. **Mst. Sultana Akhter Preya:** Writing – review & editing, Visualization, Resources. **Hafsha Khanom:** Writing – review & editing, Resources. **Sharmin Asha:** Writing – review & editing. **Md. Mostafa Kamal:** Writing – review & editing, Visualization. **Bappa Kumar Mondal:** Writing – review & editing. **Tanvir Ahmad:** Writing – review & editing, Validation.

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Data availability

Data will be made available on request.

References

[1] A. Vignesh, T.C. Amal, A. Sarvalingam, K. Vasanth, A review on the influence of nutraceuticals and functional foods on health, Food Chemistry Advances 5 (Dec. 2024) 100749, https://doi.org/10.1016/j.focha.2024.100749.
[2] M. Jendyose, Development of functional foods with enhanced health benefits, J. Food Sci. 5 (2) (May 2024) 29–42, https://doi.org/10.47941/jfs.1846.
[3] A.M. Kokande, K.R. Surana, S.K. Mahajan, E.D. Ahire, S.J. Patil, Functional foods for microbial infections, in: Applications of Functional Foods in Disease Prevention, Apple Academic Press, New York, 2023, pp. 165–189, https://doi.org/10.1201/9781003395737-9.
[4] J. Torres-Vanegas, et al., Effect of Omega 3 Fatty Acids on Inflammation Resolution in Pa-Tients with Obesity: a Randomized Placebo-Controlled Trial, Jun. 29, 2024, https://doi.org/10.20944/preprints202406.2041.v1.
[5] M. Nassar, A. Jaffery, B. Ibrahim, B. Baraka, H. Abosheaishaa, The multidimensional benefits of eicosapentaenoic acid: from heart health to inflammatory control, Egypt J Intern Med 35 (1) (Dec. 2023) 81, https://doi.org/10.1186/s43162-023-00265-6.
[6] A. Brandt, et al., Short-term intake of fiber-rich oat bran but not spelt bran flake mix lowers bacterial endotoxin levels and improves health parameters in healthy, normal weight, young to middle-aged women, J. Funct.Foods 112 (Jan. 2024) 105929, https://doi.org/10.1016/j.jff.2023.105929.
[7] N.D. Kyazimova, V.V. Kornyakova, Influence of polyphenolic compounds on human health and the course of a number of diseases, Scientific Bulletin of the Omsk State Medical University 4 (1) (May 2024) 87–91, https://doi.org/10.61634/2782-3024-2024-13-87-91.
[8] B.L. Nagar, et al., The role of bio-fortification in enhancing the nutritional quality of vegetables: a review, Adv. Res. 25 (4) (May 2024) 64–77, https://doi.org/10.9734/air/2024/v25i41082.
[9] N. Kaur, A. Agarwal, M. Sabharwal, Food fortification strategies to deliver nutrients for the management of iron deficiency anaemia, Curr. Res. Food Sci. 5 (2022) 2094–2107, https://doi.org/10.1016/j.crfs.2022.10.020.
[10] A.C. Grasso, J.J.F. Besselink, M. Tyszler, M.J. Bruins, The potential of food fortification as an enabler of more environmentally sustainable, nutritionally adequate diets, Nutrients 15 (11) (May 2023) 2473, https://doi.org/10.3390/nu15112473.
[11] A. Sharma, et al., Addressing Hidden Hunger via Improving Soil Health and Crop Nutrients Through Nanofortification, 2024, pp. 90–108, https://doi.org/10.4018/979-8-3693-1471-5.ch006.
[12] K. Ramani, Fortification IN dairy technology: BRIDGING nutrient gaps and IMPROVING public health, in: Futuristic Trends in Agriculture Engineering & Food Sciences *Volume* 3 Book 11, Iterative International Publishers, Selfypage Developers Pvt Ltd, 2024, pp. 204–229, https://doi.org/10.58532/V3BCAG11P8CH2.
[13] A. Thakur, R. Sharma, R. Rajput, Food fortification to combat micronutrient Deficiencies- A review, Current Journal of Applied Science and Technology 42 (47) (Dec. 2023) 66–79, https://doi.org/10.9734/cjast/2023/v42i474317.
[14] E.N. Pearce, M.B. Zimmermann, The prevention of iodine deficiency: a history, Thyroid 33 (2) (Feb. 2023) 143–149, https://doi.org/10.1089/thy.2022.0454.
[15] J. Fanzo, R. McLaren, A. Bellows, B. Carducci, Challenges and opportunities for increasing the effectiveness of food reformulation and fortification to improve dietary and nutrition outcomes, Food Policy 119 (Aug. 2023) 102515, https://doi.org/10.1016/j.foodpol.2023.102515.
[16] O. Dary, M. Guamuch-Castañeda, J.O. Mora, Food fortification: technological aspects, in: Encyclopedia of Human Nutrition, Elsevier, 2023, pp. 339–350, https://doi.org/10.1016/B978-0-12-821848-8.00058-5.
[17] Unicef, Institute of Public Health Nutrition Directorate General of Health Services Ministry of Health and Family Welfare Government of the People's Republic of Bangladesh national strategy on prevention and control of micronutrient deficiencies, bangladesh (2015-2024), 2023. Accessed: Jul. 15, 2025. [Online]. Available: https://www.unicef.org/bangladesh/media/4646/file/NMDCS%20Final.pdf%20.pdf.
[18] M. Todkar, R. Nagarale, S. Anjarlekar, S. Muluk, R. Nadkar, G. Singh, Food fortification with anticariogenic agents: a comprehensive review, Int. J. Appl. Decis. Sci. 8 (2) (Apr. 2022) 341–344, https://doi.org/10.22271/oral.2022.v8.i2e.1529.
[19] L. Mayurnikova, A. Koksharov, T. Krapiva, S. Novoselov, Food fortification as a preventive factor of micronutrient deficiency, Food Process: Techniques and Technology 50 (1) (Mar. 2020) 124–139, https://doi.org/10.21603/2074-9414-2020-1-124-139.
[20] A. Deavenport-Saman, A. Britt, K. Smith, R.A. Jacobs, Milestones and controversies in maternal and child health: examining a brief history of micronutrient fortification in the US, J. Perinatol. 37 (11) (Nov. 2017) 1180–1184, https://doi.org/10.1038/jp.2017.121.
[21] N.B. Piccoli, et al., Rice Fortification: Its Potential for Improving Micronutrient Intake and Steps Required for Implementation at Scale, 2012, https://doi.org/10.1177/15648265120334s312.
[22] T. Scott-Smith, Beyond the 'raw' and the 'cooked': a history of fortified blended foods, Disasters 39 (s2) (Oct. 2015), https://doi.org/10.1111/disa.12156.
[23] O.O. Ben, M.O. Blessing, O. Blessing, Progress in food fortification in Nigeria - historical overview, current issues, consumer perceptions and awareness, and the need for additional vehicles, Food Science & Nutrition Research 6 (2) (Dec. 2023), https://doi.org/10.33425/2641-4295.1071.
[24] S. Sishagn, S. Lewoye, Innovations in the fortification of bread with plant-based proteins, International Journal of Agriculture and Nutrition 6 (1) (Jan. 2024) 85–87, https://doi.org/10.33545/26646064.2024.v6.i1b.143.
[25] T.V. Yuraskina, E.N. Sokolova, N.A. Fursova, E.M. Serba, An innovative approach to food fortification using baker's yeast, Food systems 6 (4) (Jan. 2024) 554–560, https://doi.org/10.21323/2618-9771-2023-6-4-554-560.
[26] D. Dehnad, et al., Recent advances in iron encapsulation and its application in food fortification, Crit. Rev. Food Sci. Nutr. 64 (33) (Dec. 2024) 12685–12701, https://doi.org/10.1080/10408398.2023.2256004.
[27] Y.Y. Jiang, Effect of B vitamins-fortified foods on primary school children in beijing, Asia Pac. J. Publ. Health 18 (2) (2006), https://doi.org/10.1177/10105395060180020401.
[28] P.K. Mathur, et al., Beneficial effects of folic acid fortification in the prevention of Spina Bifida and reducing the orthopaedic procedures: a narrative review of the

current literature, Journal of Orthopaedic Reports 2 (3) (Sep. 2023) 100175, https://doi.org/10.1016/j.jorep.2023.100175.
[29] N. Echegaray, et al., Recent advances in food products fortification with anthocyanins, Crit. Rev. Food Sci. Nutr. 62 (6) (Feb. 2022) 1553–1567, https://doi.org/10.1080/10408398.2020.1844141.
[30] H.S.O. Darko, L. Ismaiel, B. Fanesi, D. Pacetti, P. Lucci, Current trends in food processing By-Products as sources of high value-added compounds in food fortification, Foods 13 (17) (Aug. 2024) 2658, https://doi.org/10.3390/foods13172658.
[31] I. Fadhlurrohman, J. Susanto, Functional food innovation based on fermented milk products with fortification of various types of tea: a review, JITIPARI (Jurnal Ilmiah Teknologi dan Industri Pangan UNISRI) 9 (1) (Apr. 2024) 101–114, https://doi.org/10.33061/jitipari.v9i1.10221.
[32] M. Habib, K. Jan, K. Bashir, Fortification of bioactive components for the development of functional foods, in: Bioactive Components, Springer Nature Singapore, Singapore, 2023, pp. 381–401, https://doi.org/10.1007/978-981-19-2366-1_22.
[33] S. Rossi, et al., Zinc tolerance of special yeasts and lactic acid bacteria for use in the food industry, Fermentation 9 (6) (2023), https://doi.org/10.3390/fermentation9060521.
[34] U. Mahboob, et al., Community perceptions of zinc biofortified flour during an intervention Study in Pakistan, Nutrients 14 (4) (2022), https://doi.org/10.3390/nu14040817.
[35] M.J. Khan, et al., Effect of agronomically biofortified zinc flour on zinc and selenium status in resource poor settings; a randomised control trial, Proc. Nutr. Soc. 76 (OCE4) (Dec. 2017) E183, https://doi.org/10.1017/S0029665117003457.
[36] L. Maselli, S. Hekmat, Microbial vitality of probiotic milks supplemented with cereal or pseudocereal grain flours, J. Food Res. 5 (2) (Mar. 2016) 41, https://doi.org/10.5539/jfr.v5n2p41.
[37] A. Erfanian, H. Mirhosseini, B. Rasti, M. Hair-Bejo, S. Bin Mustafa, M.Y.A. Manap, Absorption and bioavailability of nano-size reduced calcium citrate fortified milk powder in ovariectomized and ovariectomized-osteoporosis rats, J. Agric. Food Chem. 63 (24) (Jun. 2015) 5795–5804, https://doi.org/10.1021/acs.jafc.5b01468.
[38] M.F. Ramadan, Introduction to cold pressed oils: green technology, bioactive compounds, functionality, and applications, in: Cold Pressed Oils, Elsevier, 2020, pp. 1–5, https://doi.org/10.1016/B978-0-12-818188-1.00001-3.
[39] B.L. Tsang, et al., Effects of foods fortified with zinc, alone or cofortified with multiple micronutrients, on health and functional outcomes: a systematic review and meta-analysis, Adv. Nutr. 12 (5) (Sep. 2021) 1821–1837, https://doi.org/10.1093/advances/nmab065.
[40] P. Prajapati, R. Sharma, Advances in food fortification: ensuring a healthier humanity, types, and analytical methods, Current Trends in Pharmacy and Pharmaceutical Chemistry 6 (3) (Sep. 2024) 76–83, https://doi.org/10.18231/j.ctppc.2024.021.
[41] Lalarukh, et al., Microencapsulation: an innovative technology in modern science, Polym. Adv. Technol. 36 (1) (Jan. 2025), https://doi.org/10.1002/pat.70066.
[42] M. Paul, et al., A review on biofortification of crops: a nutritional strategy for combating malnutrition, Eur J Nutr Food Saf 16 (11) (Nov. 2024) 63–77, https://doi.org/10.9734/ejnfs/2024/v16i111577.
[43] O.Y. Famuyide, J. Lubaale, C. Ndiaye, K.G. Duodu, J.R.N. Taylor, Effect of extrusion cooking in combination with food-to-food fortification on the mineral bioaccessibility of african-type pearl millet-based porridge, NFS Journal 34 (Mar. 2024) 100165, https://doi.org/10.1016/j.nfs.2024.100165.
[44] M.A. Ilemobayo, K.J. Kone, Nutritional compositions and sensory evaluation of fermented maize and Millet fortified with crayfish and soybeans for the production of infant food, AgriHealth: Journal of Agri-food, Nutrition and Public Health 5 (1) (Feb. 2024) 10, https://doi.org/10.20961/agrihealth.v5i1.79364.
[45] Y. Li, X. Huang, Y. Yang, A. Mulati, J. Hong, J. Wang, The effects of cold-plasma technology on the quality properties of fresh-cut produce: a review, Foods 14 (2) (Jan. 2025) 149, https://doi.org/10.3390/foods14020149.
[46] A. Karnwal, G. Kumar, R. Singh, M. Selvaraj, T. Malik, A.R.M. Al Tawaha, Natural biopolymers in edible coatings: applications in food preservation, Food Chem. X 25 (Jan. 2025) 102171, https://doi.org/10.1016/j.fochx.2025.102171.
[47] Madhuritha Rokkam, Anil Kumar Vadaga, A brief review on the Current trends in microencapsulation, Journal of Pharma Insights and Research 2 (3) (Jun. 2024) 108–114, https://doi.org/10.69613/4ca2eh85.
[48] F.A. Tamboli, et al., Nano nutraceuticals: revolutionizing the future of health supplements, Biomedical and Pharmacology Journal 18 (1) (Mar. 2025) 459–470, https://doi.org/10.13005/bpj/3100.
[49] Z. Qin, et al., Advances in 3D and 4D printing of gel-based foods: mechanisms, applications, and future directions, Gels 11 (2) (Jan. 2025) 94, https://doi.org/10.3390/gels11020094.
[50] Y. Zhao, M. Zhang, B. Bhandari, C. Li, Development of special nutritional balanced food 3D printing products based on the mixing of animals/plants materials: research progress, applications, and trends, Crit. Rev. Food Sci. Nutr. (Feb. 2025) 1–25, https://doi.org/10.1080/10408398.2025.2457420.
[51] J. Spieldenner, The Role of Food Fortification in Addressing Iron Deficiency in Infants and Young Children, 2016, pp. 211–223, https://doi.org/10.1159/000442107.
[52] S. Junaid-ur-Rahman, et al., Rice: a potential vehicle for micronutrient fortification, Clinical Phytoscience 8 (1) (Jun. 2022) 14, https://doi.org/10.1186/s40816-022-00342-3.
[53] E.R. Nandeep, et al., Implementation, delivery, and utilization of iron fortified rice supplied through public distribution system across different states in India: an exploratory mixed-method study, PLOS Global Public Health 4 (8) (Aug. 2024) e0003533, https://doi.org/10.1371/journal.pgph.0003533.
[54] D. Hoffman, P. dos Leffa, C. Sangalli, J. Valmórbida, A. Dornelles, M. Vitolo, Impact of fortified ultra-processed foods on risk of anemia: a new perspective for pediatric nutrition, Curr. Dev. Nutr. 4 (Jun. 2020) nzaa053_046, https://doi.org/10.1093/cdn/nzaa053_046.
[55] A. Argaw, et al., Fortified balanced energy–protein supplementation during pregnancy and lactation and infant growth in rural Burkina Faso: a 2 × 2 factorial individually randomized controlled trial, PLoS Med. 20 (2) (Feb. 2023) e1004186, https://doi.org/10.1371/journal.pmed.1004186.
[56] K.D. Cashman, Vitamin D fortification of foods – sensory, acceptability, cost, and public acceptance considerations, J. Steroid Biochem. Mol. Biol. 239 (May 2024) 106494, https://doi.org/10.1016/j.jsbmb.2024.106494.
[57] K.S. Crider, et al., Folic acid and the prevention of birth defects: 30 years of opportunity and controversies, Annu. Rev. Nutr. 42 (1) (Aug. 2022) 423–452, https://doi.org/10.1146/annurev-nutr-043020-091647.
[58] A. Argaw, et al., Fortified balanced energy–protein supplementation during pregnancy and lactation and infant growth in rural Burkina Faso: a 2 × 2 factorial individually randomized controlled trial, PLoS Med. 20 (2) (Feb. 2023) e1004186, https://doi.org/10.1371/journal.pmed.1004186.
[59] M. Hiligsmann, N. Burlet, P. Fardellone, N. Al-Daghri, J.-Y. Reginster, Public health impact and economic evaluation of vitamin D-fortified dairy products for fracture prevention in France, Osteoporos. Int. 28 (3) (Mar. 2017) 833–840, https://doi.org/10.1007/s00198-016-3786-1.
[60] V.B. Rodrigues, E.N. da Silva, A.M. dos Santos, L.M.P. Santos, Prevented cases of neural tube defects and cost savings after folic acid fortification of flour in Brazil, PLoS One 18 (2) (Feb. 2023) e0281077, https://doi.org/10.1371/journal.pone.0281077.
[61] S. Gupta, et al., Impact of consuming zinc-biofortified wheat flour on the growth and morbidity status of adolescent girls: a cluster randomised, double blind, controlled trial, Proc. Nutr. Soc. 81 (OCE5) (Oct. 2022) E171, https://doi.org/10.1017/S002966512200204X.
[62] F. Knight, et al., Including calcium-fortified water or flour in modeled diets based on local foods could improve calcium intake for women, adolescent girls, and young children in Bangladesh, Uganda, and Guatemala, Ann. N. Y. Acad. Sci. 1526 (1) (Aug. 2023) 84–98, https://doi.org/10.1111/nyas.15032.
[63] B. Wang, D. Li, C. Peng, J. Hong, Y. Wu, Dietary omega-3 intake and cognitive function in older adults, Int. J. Psychiatr. Med. (Sep. 2024), https://doi.org/10.1177/00912174241284925.
[64] Sandjaja, et al., Vitamin A-fortified cooking oil reduces vitamin A deficiency in infants, young children and women: results from a programme evaluation in Indonesia, Public Health Nutr. 18 (14) (Oct. 2015) 2511–2522, https://doi.org/10.1017/S136898001400322X.
[65] B.A. Winje, et al., Does early vitamin B 12 supplementation improve neurodevelopment and cognitive function in childhood and into school age: a study protocol for extended follow-ups from randomised controlled trials in India and Tanzania, BMJ Open 8 (2) (Feb. 2018) e018962, https://doi.org/10.1136/bmjopen-2017-018962.
[66] E.C. Keats, C. Oh, T. Chau, D.S. Khalifa, A. Imdad, Z.A. Bhutta, Effects of vitamin and mineral supplementation during pregnancy on maternal, birth, child health and development outcomes in low- and middle-income countries: a systematic review, Campbell Systematic Reviews 17 (2) (Jun. 2021), https://doi.org/10.1002/cl2.1127.
[67] S. Næss, et al., Iodine nutrition and iodine supplement initiation in Association with thyroid function in mildly-to-moderately iodine-deficient pregnant and postpartum women, J. Nutr. 151 (10) (Oct. 2021) 3187–3196, https://doi.org/10.1093/jn/nxab224.
[68] S. Censi, et al., The effects of iodine supplementation in pregnancy on iodine status, Thyroglobulin levels and thyroid function parameters: results from a randomized controlled clinical trial in a mild-to-moderate iodine deficiency area, Nutrients 11 (11) (Nov. 2019) 2639, https://doi.org/10.3390/nu11112639.
[69] R. Saini, H.S. Saini, S. Verma, A. Verma, Biofortification of rice to augment iron availability for better health of population, International Journal of Environment and Climate Change (May 2022) 390–404, https://doi.org/10.9734/ijecc/2022/v12i1030811.
[70] E.R. Nandeep, et al., Implementation, delivery, and utilization of iron fortified rice supplied through public distribution system across different states in India: an exploratory mixed-method study, PLOS Global Public Health 4 (8) (Aug. 2024) e0003533, https://doi.org/10.1371/journal.pgph.0003533.
[71] J.M. Nole-Jaramillo, et al., Evaluation of the physicochemical, bioactive, and sensory properties of yogurt fortified with microencapsulated iron, Applied Food Research 4 (2) (Dec. 2024) 100525, https://doi.org/10.1016/j.afres.2024.100525.
[72] F.M. Yunus, et al., Consumption of iron-fortified lentils is protective against declining iron status among adolescent girls in Bangladesh: evidence from a community-based Double-Blind, cluster-randomized controlled trial, J. Nutr. 154 (5) (May 2024) 1686–1698, https://doi.org/10.1016/j.tjnut.2024.03.005.
[73] K. El Hoss, M. Salla, S. Khaled, M. Krayem, H.F. Hassan, S. El Khatib, Vitamin D fortification in lebanese bread: impact on sensory attributes, consumer perception and public acceptance, Applied Food Research 4 (2) (Dec. 2024) 100502, https://doi.org/10.1016/j.afres.2024.100502.
[74] Q. Wang, et al., Calcium-fortified fresh milk ameliorates postmenopausal osteoporosis via regulation of bone metabolism and gut microbiota in ovariectomized rats, Food Sci. Hum. Wellness 13 (3) (May 2024) 1258–1270, https://doi.org/10.26599/FSHW.2022.9250105.

[75] J.K. Das, et al., Efficacy of Zinc Fortified and Fermented Wheat Flour (EZAFFAW): a randomized controlled trial protocol, PLoS One 19 (6) (Jun. 2024) e0304462, https://doi.org/10.1371/journal.pone.0304462.
[76] S. Vasto, L. Sabatino, C. Santalucia, A. Sciara, S. Baldassano, Could bio-fortification of vegetables with iodine represent a tool to boost the immune System? A pilot Study on human health, in: The 2nd International Electronic Conference on Nutrients, MDPI, Basel Switzerland, Mar. 2022, p. 11, https://doi.org/10.3390/IECN2022-12400.
[77] S. Racedo, J. Villena, S. Salva, S. Alvarez, Influence of yogurt consumption on the respiratory immune response, Food Agric. Immunol. 20 (3) (Sep. 2009) 231–244, https://doi.org/10.1080/09540100903061659.
[78] C. Yajnik, et al., Efficacy of B 12 Fortified Nutrient bar and Yogurt in Improving Plasma B 12 Concentrations – Results from Two Double Blind Randomised Placebo Controlled Trials, Jan. 04, 2021, https://doi.org/10.1101/2021.01.01.21249112.
[79] L.F. Călinoiu, et al., In situ fortification of cereal by-products with vitamin B12: an eco-sustainable approach for food fortification, Food Chem. 460 (Dec. 2024) 140766, https://doi.org/10.1016/j.foodchem.2024.140766.
[80] F. Nyamete, N. Majaliwa, L. Chove, Food-Based intervention for boosting micronutrient status and health - a comprehensive review, World Journal of Food Science and Technology 8 (1) (Mar. 2024) 23–34, https://doi.org/10.11648/j.wjfst.20240801.13.
[81] Muhammad Usman Zafar, Qing Ping, Shehreen Khan, Tong Chen, Muhammad Umar Zafar, Arbab Rauf, IS functional food BENEFICIAL to HUMAN being? A QUANTITATIVE study of Punjab PROVINCE, Pakistan, Khaldunia - Journal of Social Sciences 2 (1) (Dec. 2022) 49–65, https://doi.org/10.36755/khaldunia.v2i1.44.
[82] R. Begum, M. Hasan, S. Akter, M. Rahman, Fortified edible oils in Bangladesh: a study on vitamin A fortification and physicochemical properties, Heliyon 10 (3) (Feb. 2024) e25489, https://doi.org/10.1016/j.heliyon.2024.e25489.
[83] R.W. Basrowi, C. Dilantika, Optimizing iron adequacy and absorption to prevent iron deficiency anemia: the role of combination of fortified iron and vitamin C, World Nutrition Journal 5 (S1) (Jun. 2021) 33–39, https://doi.org/10.25220/WNJ.V05.S1.0005.
[84] A.C. Ross, Vitamin A: physiology, dietary sources and requirements, in: Encyclopedia of Human Nutrition, Elsevier, 2023, pp. 471–481, https://doi.org/10.1016/B978-0-12-821848-8.00082-2.
[85] M.N. Abed, F.A. Alassaf, M.E. Qazzaz, Exploring the interplay between vitamin D, insulin resistance, obesity and skeletal health, J Bone Metab 31 (2) (May 2024) 75–89, https://doi.org/10.11005/jbm.2024.31.2.75.
[86] X. Chen, W. Zhang, S.Y. Quek, L. Zhao, Flavor–Food Ingredient Interactions in Fortified or Reformulated Novel Food: Binding Behaviors, Manipulation Strategies, Sensory Impacts, and Future Trends in Delicious and Healthy Food Design, 2023, https://doi.org/10.1111/1541-4337.13195.
[87] S.M.T. Gharibzahedi, M. Moghadam, J. Amft, A. Tolun, G. Hasabnis, Z. Altintas, Recent advances in dietary sources, health benefits, emerging encapsulation methods, food fortification, and new sensor-based monitoring of vitamin B12: a critical review, Molecules 28 (22) (Nov. 2023) 7469, https://doi.org/10.3390/molecules28227469.
[88] C. Marques, et al., Mechanistic insights into the multiple functions of niacinamide: therapeutic implications and cosmeceutical applications in functional skincare products, Antioxidants 13 (4) (Mar. 2024) 425, https://doi.org/10.3390/antiox13040425.
[89] S. Khanna, S. Aufreiter, A.J. MacFarlane, Y.A. Shakur, D.L. O'Connor, Folate and synthetic folic acid content in Canadian fortified foods two decades after mandatory fortification, Appl. Physiol. Nutr. Metabol. 49 (9) (Sep. 2024) 1202–1209, https://doi.org/10.1139/apnm-2024-0063.
[90] R. Harika, M. Faber, F. Samuel, J. Kimiywe, A. Mulugeta, A. Eilander, Micronutrient status and dietary intake of iron, vitamin A, iodine, folate and zinc in women of reproductive Age and pregnant women in Ethiopia, Kenya, Nigeria and South Africa: a systematic review of data from 2005 to 2015, Nutrients 9 (10) (Oct. 2017) 1096, https://doi.org/10.3390/nu9101096.
[91] M.Â. Aragão, L. Pires, C. Santos-Buelga, L. Barros, R.C. Calhelha, Revitalising riboflavin: unveiling its timeless significance in human physiology and health, Foods 13 (14) (Jul. 2024) 2255, https://doi.org/10.3390/foods13142255.
[92] M. Mrowicka, J. Mrowicki, G. Dragan, I. Majsterek, The importance of thiamine (vitamin B1) in humans, Biosci. Rep. 43 (10) (Oct. 2023), https://doi.org/10.1042/BSR20230374.
[93] A.-M. Lampousi, T. Lundberg, J.E. Löfvenborg, S. Carlsson, Vitamins C, E, and β-Carotene and risk of type 2 diabetes: a systematic review and meta-analysis, Adv. Nutr. 15 (5) (Nov. 2024) 100211, https://doi.org/10.1016/j.advnut.2024.100211.
[94] D. Henao-González, D. David, J. Torres-Oquendo, P.J. do A. Sobral, O. Vega-Castro, Design and optimization of a strawberry-based dispersion to produce a spray drying functional powdered product, fortified with folic acid and zinc, Food Bioprod. Process. 147 (Sep. 2024) 105–114, https://doi.org/10.1016/j.fbp.2024.05.017.
[95] C. Hoppe, et al., The use of whey or skimmed milk powder in fortified blended foods for vulnerable groups, J. Nutr. 138 (1) (Jan. 2008) 145S–161S, https://doi.org/10.1093/jn/138.1.145S.
[96] S.K. Bonik, S.T. Tamanna, T.A. Happy, Md N. Haque, S. Islam, Md O. Faruque, Formulation and evaluation of cereal-based breads fortified with natural prebiotics from green banana, moringa leaves powder and soya powder, Applied Food Research 4 (1) (Jun. 2024) 100377, https://doi.org/10.1016/j.afres.2023.100377.
[97] G. Añorve-Valdez, A.D. Quezada-Sánchez, F. Mejía-Rodríguez, A. García-Guerra, L.M. Neufeld, Fortified food supplementation in children with reduced dietary energy and micronutrients intake in Southern Mexico, Nutr. J. 17 (1) (Dec. 2018) 76, https://doi.org/10.1186/s12937-018-0385-3.
[98] J.G.S. Silva, A.P. Rebellato, J.S. de Abreu, R. Greiner, J.A.L. Pallone, Impact of the fortification of a rice beverage with different calcium and iron sources on calcium and iron bioaccessibility, Food Res. Int. 161 (Nov. 2022) 111830, https://doi.org/10.1016/j.foodres.2022.111830.
[99] A. Aramburu, et al., Ultra-processed foods consumption and health-related outcomes: a systematic review of randomized controlled trials, Front. Nutr. 11 (Jun) (2024), https://doi.org/10.3389/fnut.2024.1421728.
[100] M.M. Lane, et al., Ultra-processed food exposure and adverse health outcomes: umbrella review of epidemiological meta-analyses, Br. Med. J. (Feb. 2024) e077310, https://doi.org/10.1136/bmj-2023-077310.
[101] M.N. Erlich, et al., A systematic review and meta-analysis of randomized trials of substituting soymilk for cow's milk and intermediate cardiometabolic outcomes: understanding the impact of dairy alternatives in the transition to plant-based diets on cardiometabolic health, BMC Med. 22 (1) (Aug. 2024) 336, https://doi.org/10.1186/s12916-024-03524-7.
[102] P. Milani, et al., Social marketing of a fortified staple food at Scale: generating demand for fortified rice in Brazil, J. Food Prod. Market. 23 (8) (Nov. 2017) 955–978, https://doi.org/10.1080/10454446.2016.1266546.
[103] S. Nigar, I.M. Shimul, Md S. Hossain, R. Sultana, S. Asha, A.K.O. Huq, Comparative analysis on phytonutrient properties of different fig varieties (Ficus spp.), Food Chemistry Advances 6 (Mar. 2025) 100878, https://doi.org/10.1016/j.focha.2024.100878.
[104] Y.M. Yusoff, et al., Knowledge and perception regarding safe-use of natural health products among undergraduates, Journal of Ecohumanism 3 (8) (Dec. 2024), https://doi.org/10.62754/joe.v3i8.5287.
[105] A. Sharma, D. Biloria, Understanding Social Influences in Cinema Managing Culture, Society, and Peer Influence, 2025, pp. 213–232, https://doi.org/10.4018/979-8-3693-3104-0.ch009.
[106] J. Lin, Analysis of economic factors affecting consumer purchase intentions on E-commerce live streaming platforms, Advances in Economics, Management and Political Sciences 93 (1) (Jul. 2024) 271–276, https://doi.org/10.54254/2754-1169/93/20241122.
[107] A. Thakur, R. Sharma, R. Rajput, Food fortification to combat micronutrient Deficiencies- A review, Current Journal of Applied Science and Technology 42 (47) (Dec. 2023) 66–79, https://doi.org/10.9734/cjast/2023/v42i474317.
[108] T. Durotoye, R. Yusufali, V. Ajieroh, O. Ezekannagha, Building the commitment of the private sector and leveraging effective partnerships to sustain food fortification, Food Nutr. Bull. 44 (1_suppl) (Sep. 2023) S61–S73, https://doi.org/10.1177/03795721221123699.
[109] Y. Tian, H. Zhu, L. Zhang, H. Chen, Consumer preference for nutritionally fortified eggs and impact of health benefit information, Foods 11 (8) (Apr. 2022) 1145, https://doi.org/10.3390/foods11081145.
[110] Md S. Hossain, M.A. Wazed, S. Asha, Md R. Amin, I.M. Shimul, Dietary phytochemicals in health and disease: mechanisms, clinical evidence, and Applications—A comprehensive review, Food Sci. Nutr. 13 (3) (Mar. 2025), https://doi.org/10.1002/fsn3.70101.
[111] Q.E.M. Mangwane, A. Egal, D. Oosthuizen, Impact of a nutrition knowledge intervention on knowledge and food behaviour of women within a rural community, Nutrients 16 (23) (Nov. 2024) 4107, https://doi.org/10.3390/nu16234107.
[112] M.K. Shah, M. Hajipour, Z. Sheibani, A.L. Couper, S. Sandanasamy, P. McFarlane, Effect of educational interventions on nutritional knowledge of cancer prevention based on health belief model: a systematic review, Journal of Nursing Reports in Clinical Practice 3 (3) (May 2025) 290–299, https://doi.org/10.32598/JNRCP.2407.1129.
[113] G.J. MacArthur, M. Hickman, R. Campbell, Qualitative exploration of the intersection between social influences and cultural norms in relation to the development of alcohol use behaviour during adolescence, BMJ Open 10 (3) (Mar. 2020) e030556, https://doi.org/10.1136/bmjopen-2019-030556.
[114] T. Raj, N. Singh, A. Nanda, Optimizing nutritional content in fortified rice cake: phytochemical and sensory evaluation, Current Journal of Applied Science and Technology 43 (9) (Sep. 2024) 67–77, https://doi.org/10.9734/cjast/2024/v43i94431.
[115] Md S. Hossain, et al., Flavor and Well-Being: a comprehensive review of food choices, nutrition, and health interactions, Food Sci. Nutr. 13 (5) (May 2025), https://doi.org/10.1002/fsn3.70276.
[116] T. Izhar, M. Chakraborty, D. Singh, K. Prasad, E. Ahmad, A. Kumar, Study of high iron and high zinc contents varieties of rice in Jharkhand condition through biofortification, International Journal of Advanced Biochemistry Research 8 (4) (Jan. 2024) 388–390, https://doi.org/10.33545/26174693.2024.v8.i4e.995.
[117] K.D. Cashman, C.M. O'Neill, Strategic food vehicles for vitamin D fortification and effects on vitamin D status: a systematic review and meta-analysis of randomised controlled trials, J. Steroid Biochem. Mol. Biol. 238 (Apr. 2024) 106448, https://doi.org/10.1016/j.jsbmb.2023.106448.
[118] B. Naik, et al., Biofortification as a solution for addressing nutrient deficiencies and malnutrition, Heliyon 10 (9) (May 2024) e30595, https://doi.org/10.1016/j.heliyon.2024.e30595.
[119] L.L. Diosady, M.G.V. Mannar, K. Krishnaswamy, Improving the lives of millions through new double fortification of salt technology, Matern. Child Nutr. 15 (S3) (May 2019), https://doi.org/10.1111/mcn.12773.
[120] D. Rai, C. Chaudhary, A. Khatak, S. Banyal, A sustainable approach to combat micronutrient deficiencies and ensure global food security through

biofortification, Eur J Nutr Food Saf 16 (4) (Mar. 2024) 15–30, https://doi.org/10.9734/ejnfs/2024/v16i41404.

[121] J. Webster, et al., Implementing effective salt reduction programs and policies in low- and middle-income countries: learning from retrospective policy analysis in Argentina, Mongolia, South Africa and Vietnam, Public Health Nutr. 25 (3) (Mar. 2022) 805–816, https://doi.org/10.1017/S136898002100344X.

[122] P.R. Pehrsson, et al., Iodine in foods and dietary supplements: a collaborative database developed by NIH, FDA and USDA, J. Food Compos. Anal. 109 (Jun. 2022) 104369, https://doi.org/10.1016/j.jfca.2021.104369.

[123] D.L. Gilliland, et al., Assessment of regulatory compliance testing for vitamin D in infant Formula—Impact of delegated regulation (EU) 2019/828, J. AOAC Int. 105 (5) (Sep. 2022) 1360–1366, https://doi.org/10.1093/jaoacint/qsac060.

[124] L. Thurston, B. Borman, C. Bower, Mandatory fortification with folic acid for the prevention of neural tube defects: a case study of Australia and New Zealand, Childs Nerv. Syst. 39 (7) (Jul. 2023) 1737–1741, https://doi.org/10.1007/s00381-022-05823-x.

[125] A. Khare, S. Samudre, A. Arora, Sneak-Peek into Iron Deficiency Anemia in India: the Need for Food-based Interventions and Enhancing Iron Bioavailability, 2022, https://doi.org/10.1016/j.foodres.2022.111927.

[126] M. Zuma, U. Kolanisi, A. Modi, The potential of integrating provitamin A-Biofortified maize in smallholder farming systems to reduce malnourishment in South Africa, Int. J. Environ. Res. Publ. Health 15 (4) (Apr. 2018) 805, https://doi.org/10.3390/ijerph15040805.

[127] V.B. Rodrigues, E.N. da Silva, A.M. dos Santos, L.M.P. Santos, Prevented cases of neural tube defects and cost savings after folic acid fortification of flour in Brazil, PLoS One 18 (2) (Feb. 2023) e0281077, https://doi.org/10.1371/journal.pone.0281077.

[128] L. Fan, et al., How to decide the iodine content in salt for a Country—China as an example, Nutrients 14 (21) (Nov. 2022) 4606, https://doi.org/10.3390/nu14214606.

[129] A. Shahandeh, B.V. Bui, D.I. Finkelstein, C.T.O. Nguyen, Effects of excess iron on the retina: insights from clinical cases and animal models of iron disorders, Front. Neurosci. 15 (Feb. 2022), https://doi.org/10.3389/fnins.2021.794809.

[130] D. Turck, et al., Scientific opinion on the tolerable upper intake level for preformed vitamin A and β-carotene, EFSA J. 22 (6) (Jun. 2024), https://doi.org/10.2903/j.efsa.2024.8814.

[131] E. Piskin, D. Cianciosi, S. Gulec, M. Tomas, E. Capanoglu, Iron absorption: factors, limitations, and improvement methods, ACS Omega 7 (24) (Jun. 2022) 20441–20456, https://doi.org/10.1021/acsomega.2c01833.

[132] M.H. de Jong, E.L. Nawijn, J. Verkaik-Kloosterman, Contribution of fortified margarines and other plant-based fats to micronutrient intake in the Netherlands, Eur. J. Nutr. 61 (4) (Jun. 2022) 1893–1904, https://doi.org/10.1007/s00394-021-02757-z.

[133] L. Hooper, et al., Evidence to underpin vitamin A requirements and upper limits in children aged 0 to 48 months: a scoping review, Nutrients 14 (3) (Jan. 2022) 407, https://doi.org/10.3390/nu14030407.

[134] L. Allen, B. De Benoist, O. Dary, and R. Hurrell, "Guidelines on Food Fortification with Micronutrients A T.".

[135] C. Burke, R. Allen, Complications of cesarean birth: clinical recommendations for prevention and management, MCN Am. J. Matern./Child Nurs. 45 (2) (2020), https://doi.org/10.1097/NMC.0000000000000598.

[136] D. Dehnad, et al., Recent advances in iron encapsulation and its application in food fortification, Crit. Rev. Food Sci. Nutr. 64 (33) (Dec. 2024) 12685–12701, https://doi.org/10.1080/10408398.2023.2256004.

[137] A. Kumari, A.K. Chauhan, Iron nanoparticles as a promising compound for food fortification in iron deficiency anemia: a review, J. Food Sci. Technol. 59 (9) (Sep. 2022) 3319–3335, https://doi.org/10.1007/s13197-021-05184-4.

[138] M. Heffernan, et al., Effectiveness of a fortified drink in improving B vitamin biomarkers in older adults: a controlled intervention trial, Nutr. Metab. 18 (1) (Dec. 2021) 104, https://doi.org/10.1186/s12986-021-00630-8.

[139] J. Dhankhar, P. Kundu, R. Mehla, Nanoformulation: a promising approach towards food fortification, in: Nanotechnology Horizons in Food Process Engineering, Apple Academic Press, New York, 2023, pp. 229–253, https://doi.org/10.1201/9781003305378_10.

[140] P. Pandey, N. Minocha, Nano-Fortifying the future plate: a critical review of nanotechnology applications in food enrichment, Curr. Nutr. Food Sci. 20 (Jul. 2024), https://doi.org/10.2174/0115734013308306240616081605.

[141] F. Artés-Hernández, N. Castillejo, L. Martínez-Zamora, G.B. Martínez-Hernández, Phytochemical fortification in fruit and vegetable beverages with green technologies, Foods 10 (11) (Oct. 2021) 2534, https://doi.org/10.3390/foods10112534.

[142] O. Santosh, et al., Novel Food Product Development Through food-to-food Fortification with Nutrient and Bioactive Compound-Rich Bamboo Shoot, 2023, pp. 67–87, https://doi.org/10.1007/978-981-99-0015-2_4.

[143] M. Bansal, A. Poonia, S.R.P. Kolluri, Vasundhara, Introduction on bioactive compounds, sources and their potential applications, in: Bioactive Components, Springer Nature Singapore, Singapore, 2023, pp. 3–26, https://doi.org/10.1007/978-981-19-2366-1_1.

[144] A. Afreen, Z. Ahmed, N. Anjum, Novel nutraceutical compounds, in: Therapeutic, Probiotic, and Unconventional Foods, Elsevier, 2018, pp. 201–226, https://doi.org/10.1016/B978-0-12-814625-5.00012-1.

[145] M. Nag, et al., Functional foods: formulation, fortification, and combating COVID-19, in: The Functional Foods, Apple Academic Press, New York, 2024, pp. 117–148, https://doi.org/10.1201/9781032684055-8.

[146] P. Garcia-Oliveira, et al., Macroalgae as an alternative source of nutrients and compounds with bioactive potential, in: The 1st International Electronic Conference on Food Science and Functional Foods, MDPI, Basel Switzerland, Nov. 2020, p. 46, https://doi.org/10.3390/foods_2020-07648.

[147] G. Eksi, S. Kurbanoglu, S.A. Ozkan, Fortification of functional and medicinal beverages with botanical products and their analysis, in: Engineering Tools in the Beverage Industry, Elsevier, 2019, pp. 351–404, https://doi.org/10.1016/B978-0-12-815258-4.00012-3.

[148] V. Romina Alina, et al., Food fortification through innovative technologies, Food Eng. (2019), https://doi.org/10.5772/intechopen.82249. IntechOpen.

[149] M.C. Lallawmkimi, et al., Innovative approaches in crop genetic engineering for sustainable agriculture: a review, J Adv Biol Biotechnol 27 (8) (Jul. 2024) 615–631, https://doi.org/10.9734/jabb/2024/v27i81177.

[150] B.K. Reddy, et al., A comprehensive review on biofortification in vegetable crops, J Adv Biol Biotechnol 27 (8) (Aug. 2024) 1448–1458, https://doi.org/10.9734/jabb/2024/v27i81267.

[151] A.K. Bhardwaj, S. Chejara, K. Malik, R. Kumar, A. Kumar, R.K. Yadav, Agronomic biofortification of food crops: an emerging opportunity for global food and nutritional security, Front. Plant Sci. 13 (Dec. 2022), https://doi.org/10.3389/fpls.2022.1055278.

[152] B. Naik, et al., Biofortification as a solution for addressing nutrient deficiencies and malnutrition, Heliyon 10 (9) (May 2024) e30595, https://doi.org/10.1016/j.heliyon.2024.e30595.

[153] N. Tanwar, S.S. Arya, J.E. Rookes, D.M. Cahill, S.K. Lenka, K.C. Bansal, Prospects of chloroplast metabolic engineering for developing nutrient-dense food crops, Crit. Rev. Biotechnol. 43 (7) (Oct. 2023) 1001–1018, https://doi.org/10.1080/07388551.2022.2092717.

[154] X. Chen, W. Zhang, S.Y. Quek, L. Zhao, Flavor–food ingredient interactions in fortified or reformulated novel food: binding behaviors, manipulation strategies, sensory impacts, and future trends in delicious and healthy food design, Compr. Rev. Food Sci. Food Saf. 22 (5) (Sep. 2023) 4004–4029, https://doi.org/10.1111/1541-4337.13195.

[155] G. Chinnici, C. Zarba, D. Privitera, A. Matarazzo, A. Scuderi, Food attributes of fortified foods: an analysis of consumption behaviour, Dec. 2023, pp. 223–230, https://doi.org/10.5593/sgem2023V/6.2/s25.28.

[156] R. Embling, et al., Exploring consumer beliefs about novel fortified foods: a focus group study with UK-based older and younger adult consumers, Appetite 193 (Feb. 2024) 107139, https://doi.org/10.1016/j.appet.2023.107139.

[157] R. Tolve, B. Simonato, Fortified cereal-based foodstuffs: technological, sensory, and nutritional properties, Foods 13 (8) (Apr. 2024) 1182, https://doi.org/10.3390/foods13081182.

[158] T. Varzakas, S. Smaoui, Global food security and sustainability issues: the road to 2030 from nutrition and sustainable healthy diets to food systems change, Foods 13 (2) (Jan. 2024) 306, https://doi.org/10.3390/foods13020306.

[159] Y. Papanikolaou, V.L.I. Fulgoni, The role of fortified and enriched refined grains in the US dietary pattern: a NHANES 2009–2016 modeling analysis to examine nutrient adequacy, Front. Nutr. 8 (Sep. 2021), https://doi.org/10.3389/fnut.2021.655464.

[160] M. Barone, F. D'Amico, P. Brigidi, S. Turroni, Gut microbiome–micronutrient interaction: the key to controlling the bioavailability of minerals and vitamins? Biofactors 48 (2) (Mar. 2022) 307–314, https://doi.org/10.1002/biof.1835.

[161] K. Fadly, N.N. Chaerunnisa, Fortified ultra-processed foods as an intervention in vulnerable populations to address nutrient deficiencies: a mini review, Jurnal Gizi dan Pangan 18 (Supp.1) (Dec. 2023) 128–130, https://doi.org/10.25182/jgp.2023.18.Supp.1.128-130.

[162] A. Kiosia, et al., The double burden of malnutrition in individuals: identifying key challenges and re-thinking research focus, Nutr. Bull. 49 (2) (Jun. 2024) 132–145, https://doi.org/10.1111/nbu.12670.

[163] A.C. Grasso, J.J.F. Besselink, M. Tyszler, M.J. Bruins, The potential of food fortification as an enabler of more environmentally sustainable, nutritionally adequate diets, Nutrients 15 (11) (May 2023) 2473, https://doi.org/10.3390/nu15112473.

[164] S. Gaikwad, P. Awatade, Y. Sirdeshmukh, C. Prasad, Precision nutrition through smart wearable technology tailored solutions for personalized health enhancement, in: 2024 IEEE International Conference on Contemporary Computing and Communications (Inc4), IEEE, Mar. 2024, pp. 1–6, https://doi.org/10.1109/InC460750.2024.10649111.

[165] L. Manikam, et al., Exploring the feasibility of a culturally tailored infant nutrition intervention: a qualitative study of perspectives from community facilitators and attendees in a pilot randomised controlled trial – nurture early for Optimal Nutrition (NEON) in East London, BMJ Public Health 2 (2) (Oct. 2024) e001358, https://doi.org/10.1136/bmjph-2024-001358.

[166] S.J.M. Osendarp, et al., Large-Scale food fortification and biofortification in Low- and middle-income countries: a review of programs, trends, challenges, and evidence gaps, Food Nutr. Bull. 39 (2) (Jun. 2018) 315–331, https://doi.org/10.1177/0379572118774229.