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A Review of Fortified Breads: Nutritional Benefits, Challenges, and Public Health Implications

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ABSTRACT

Bread is a staple food and a major energy source for many populations, especially in developing countries. However, traditional bread often lacks essential micronutrients, contributing to widespread malnutrition. The primary objective of this study is to evaluate the effectiveness, feasibility, and barriers of bread fortification as a public health strategy to reduce micronutrient deficiencies. Fortified bread, enriched with key nutrients such as iron, folic acid, vitamin D, calcium, iodine, and dietary fiber, represents an effective strategy to combat micronutrient deficiencies and improve public health outcomes. These nutrients support critical functions such as anemia prevention, immune health, bone integrity, and fetal development. Fortified bread is particularly beneficial for vulnerable populations, including children, pregnant women, and the elderly. Despite its benefits, several challenges hinder its widespread adoption. These include sensory alterations such as changes in taste and texture, increased production costs, regulatory complexity, and limited consumer awareness or acceptance. Addressing these barriers requires coordinated efforts in food technology, education, and policy support. Overall, bread fortification presents a practical and sustainable solution to enhance nutritional status and reduce the burden of diet-related diseases globally.

1. Introduction

Bread is one of the most widely consumed staple foods globally, contributing significantly to daily caloric intake, particularly in low-and middle-income countries (Weegels, 2019). In several regions, especially in parts of the Middle East, North Africa, and South Asia, bread provides over 50% of the population's daily energy intake due to its affordability, accessibility, and cultural significance. Despite its central role in human diets, conventional bread, typically produced from refined white flour, offers limited micronutritional value, often lacking essential nutrients such as iron, folic acid, vitamin D, calcium, and dietary fiber (Gómez et al., 2020). Globally, malnutrition and micronutrient deficiencies pose significant public health challenges. According to the World Health Organization (WHO), iron-deficiency anemia affects over 1.6 billion people worldwide, with the highest prevalence in women of reproductive age and young children. Vitamin D deficiency impacts nearly 1 billion individuals, contributing to rickets in children and osteoporosis in older adults (Kiani et al., 2022). In low-income regions, these deficiencies are exacerbated by monotonous diets and limited access to diverse food sources. In this context, bread, as a staple food, offers a practical

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platform for nutritional interventions and food fortification. Food fortification refers to the process of adding essential nutrients to widely consumed food items to enhance their nutritional value. Fortified breads are a prime example of this approach. Enriched breads improve overall health by containing beneficial compounds such as B vitamins, iron, calcium, zinc, and dietary fiber. Fortified breads are products in which nutrients such as vitamins, minerals, fibers, and proteins are added during the production process (Alina et al., 2019). These breads are particularly important in developing countries, where malnutrition is more prevalent. As a cost-effective and practical tool, they can be employed to address nutritional deficiencies efficiently. Food fortification, particularly of staple foods like bread, has emerged as a cost-effective strategy to address micronutrient deficiencies at the population level. Past public health successes, such as salt iodization and milk fortification with vitamin D, demonstrate the potential of fortification programs to improve health outcomes sustainably (Pellegrino et al., 2021). Past experiences have demonstrated that food fortification is a low-cost and effective method for improving nutritional status across populations. Nutrients commonly used in bread fortification include B vitamins (such as folic acid and vitamin B12), vitamin D, iron, calcium, zinc, iodine, dietary fiber, and omega-3 fatty acids (Alina et al., 2019). Each of these components plays a vital role in enhancing public health. Fortified breads are especially beneficial for vulnerable groups such as pregnant women, children, and the elderly, who have specific nutritional requirements. For example, adding folic acid to bread can help prevent neural tube defects in newborns, while iron fortification can contribute to reducing the prevalence of anemia (Shlobin et al., 2020). In addition to their nutritional benefits, fortified breads offer several other advantages. These products can contribute to improved digestive health, reduced risk of cardiovascular diseases and type 2 diabetes, enhanced immune function, and prevention of chronic conditions such as osteoporosis and anemia (Cencic & Chingwaru, 2010). Consequently, they can significantly improve consumers' quality of life. However, the production and acceptance of fortified breads face several challenges (Dwyer et al., 2015). Alterations in taste, texture, and increased production costs are among the factors that may reduce consumer acceptance, particularly in countries with limited healthcare resources (Dwyer et al., 2015). Another barrier to the widespread adoption of fortified bread is the general lack of public awareness regarding its health benefits (Chamandoost et al., 2015). Fortifying bread has the potential to reduce healthcare costs associated with malnutrition and related diseases. Despite these numerous advantages, the development of fortified bread is not without obstacles. One key challenge is the potential change in organoleptic properties-such as taste, color, and texture-which may negatively affect consumer preferences. Additionally, the higher production costs of fortified bread remain a significant barrier to its broader implementation (Dwyer et al., 2015). Consumer unawareness of the nutritional benefits of such products further limits their acceptance. Numerous studies have demonstrated that the consumption of fortified bread can lead to significant improvements in nutritional status (Nikooyeh et al., 2016; Yang & Huffman, 2011). These studies confirm the positive effects of fortification in reducing the prevalence of anemia, improving bone health, and lowering the risk of chronic diseases. Recent advancements in food technology have made it possible to incorporate nutrients into bread with minimal impact on its sensory qualities. One such innovation is the use of microencapsulation techniques, which help preserve the stability and functionality of added nutrients while maintaining desirable organoleptic characteristics. Furthermore, fortified bread can reduce the need for separate dietary supplements, thereby decreasing waste production and conserving natural resources. This makes bread fortification a sustainable strategy in the fight against malnutrition. Given the high prevalence of malnutrition in many countries and its widespread impact on health and quality of life, implementing effective solutions such as bread fortification is essential. Government support and appropriate policymaking can promote fortified bread, and measures such as subsidies for producers and increased public awareness are particularly effective. With growing public awareness and technological advancements, the consumption of fortified bread is expected to rise, making it an integral part of daily diets. This review aims to critically examine the nutritional benefits of fortified bread, assess the major challenges impeding its adoption, and explore its potential as a public health intervention. By synthesizing current evidence across different regions and nutrient targets, the review provides insight into how fortified bread can serve as an accessible, scalable solution to global malnutrition while identifying gaps and future directions for policy and practice.

2. Discussion

2.1 The concept of fortified bread

2.1.1 Definition and significance of fortified bread

Fortified breads are products in which essential nutrients, such as vitamins, minerals, dietary fiber, or other functional compounds, are added to the base flour during the production process (Nikooyeh et al., 2016). This enrichment is intended to compensate for the nutritional deficiencies typically found in conventional bread and to enhance its overall nutritional value. The concept of food fortification dates back to the 1920s, when iodine was first added to table salt as a preventive measure against goiter (Zimmermann & Windhab, 2009). Since then, food fortification has been successfully applied to other staples, including bread.

Several countries have adopted mandatory or voluntary bread fortification programs with positive public health outcomes. For example, the United States introduced folic acid fortification in enriched cereal grain products in 1998, which led to a 25-30% reduction in neural tube defects (Shlobin et al., 2020). Similarly, Australia mandated folic acid fortification in bread-making flour, demonstrating measurable improvements in maternal and child health (Saing et al., 2019). These examples highlight the potential of fortified bread as a low-cost, population-wide strategy to address nutrient deficiencies. Furthermore, the inclusion of dietary fiber can aid in improving digestive function and reducing the risk of chronic diseases such as type 2 diabetes and cardiovascular conditions (Alahmari, 2024; Kaczmarczyk et al., 2012).

2.1.2 Nutrients used in bread fortification

A variety of nutrients are utilized in the fortification of bread, each offering specific health benefits. These include B vitamins (such as folic acid, vitamin B12, and thiamine), vitamin D, essential minerals (such as calcium, iron, iodine, and zinc), dietary fiber, omega-3 fatty acids, plant-based proteins, and antioxidant compounds (Nikooyeh et al., 2016). Fortifying bread with these nutrients can significantly enhance its nutritional value and contribute to better overall health. For instance, folic acid helps reduce neural tube defects in fetuses, while iron fortification addresses iron-deficiency anemia (Shlobin et al., 2020).

2.1.3 The role of fortified bread in promoting public health

Fortified breads, due to their enriched nutritional composition, have substantial impacts on public health. These products are especially beneficial for vulnerable groups such as children, pregnant women, and the elderly. For instance, iron and folic acid fortification helps reduce the risk of anemia and developmental disorders (Alahmari, 2024). Calcium and zinc promote bone and immune health, while omega-3 fatty acids are associated with improved cardiovascular outcomes. Notably, randomized controlled trials have shown that vitamin D-fortified bread can be as effective as supplements in improving serum vitamin D levels (Nikooyeh et al., 2016).

2.1.4 Differences between fortified and conventional bread

Fortified bread differs substantially from conventional bread in nutritional composition. Conventional white bread made from refined flour typically contains minimal levels of micronutrients and fiber. For example, standard white bread contains <1 mg of iron per slice, while iron-fortified bread may provide up to 3 mg, meeting approximately 17% of the daily requirement for adult women (Man et al., 2022). Folic acid content can also increase from around 30 µg to over 100 µg per slice in fortified variants (Crider et al., 2011). In addition, fiber-enriched breads improve digestive health and blood sugar regulation, while antioxidant and protein additions enhance overall well-being. However, the effectiveness of fortified bread depends on both its nutrient content and the body's ability to absorb these nutrients. Concerns have been raised about potential interactions, such as high iron intake inhibiting zinc absorption or excess folic acid masking vitamin B12 deficiency, particularly in elderly populations (Crider et al., 2011). These issues highlight the importance of balanced formulation and targeted application.

2.2 Types of fortified breads

Fortified breads are classified into various types based on the added nutrients and their specific nutritional objectives. Each type is designed to meet particular dietary needs and improve the health of different population groups. The following is an overview of the main categories of fortified breads:

2.2.1 Breads fortified with B vitamins

B vitamins-including thiamine (B1), riboflavin (B2), niacin (B3), folic acid (B9), and vitamin B12-play essential roles in metabolic and neurological health (Korzeniowska et al., 2017). Folic acid, in particular, has been extensively fortified in bread and other cereal products. In countries like the USA, mandatory folic acid fortification has resulted in a substantial reduction in neural tube defects, demonstrating its efficacy as a public health intervention (Shlobin et al., 2020). Comparatively, vitamin B12 fortification has seen more limited implementation, in part due to its higher cost and instability during baking. Moreover, some populations may already obtain sufficient B12 through animal products, reducing the perceived need for fortification.

2.2.2 Breads fortified with vitamin D

Vitamin D fortification of bread is gaining attention, especially in countries with limited sunlight exposure. Clinical trials show that vitamin D-fortified bread can be as effective as supplements in improving serum 25(OH)D levels (Nikooyeh et al., 2016). However, implementation remains inconsistent across regions due to regulatory challenges, differences in baseline vitamin D status, and consumer perceptions of fortified foods.

2.2.3 Breads fortified with iron

Iron-fortified breads have been effective in addressing iron-deficiency anemia, especially among pregnant women and children (Diego Quintaes et al., 2017). However, iron compounds used in fortification may lead to sensory changes (e.g., metallic taste) and interact negatively with other nutrients like zinc and calcium. Despite these limitations, iron fortification remains one of the most cost-effective strategies to combat anemia. Compared to folic acid, iron shows slower, but broader, impacts on population health, as folic acid's benefits are primarily concentrated in reproductive-age women (Köken et al., 2013).

2.2.4 Breads fortified with calcium

Calcium-fortified breads serve as important alternatives for lactose-intolerant populations. While effective in increasing calcium intake, especially in postmenopausal women, the efficacy may be compromised by poor absorption rates in the presence of certain dietary inhibitors. Regional adoption is more common in countries with low dairy consumption or high osteoporosis risk (Chilek et al., 2018).

2.2.5 Breads fortified with dietary fiber

Fiber fortification improves digestive health and supports weight management. Unlike micronutrients, fiber is more resilient during baking, making it easier to implement. However, excessive fiber levels may affect bread texture and consumer acceptance, especially in cultures that prefer soft, refined bread textures (Almoumen et al., 2025).

2.2.6 Breads fortified with iodine

While iodine deficiency remains a global concern, especially in landlocked and high-altitude regions, iodized salt has remained the preferred vehicle for iodine delivery due to its cost-effectiveness, universality, and stability. Bread fortification with iodine is less common and often technically challenging because of iodine's volatility during baking and its uneven distribution in dough. Additionally, many countries already mandate the use of iodized salt in breadmaking, reducing the need for separate iodine fortification in flour (Milanesi & Brent, 2017). Nevertheless, in regions where iodized salt use is inconsistent, iodine-fortified bread may still serve as a complementary strategy.

2.2.7 Breads fortified with omega-3 fatty acids

Omega-3 fortification can contribute to cardiovascular and cognitive health. However, challenges include the stability of omega-3s during baking and their susceptibility to oxidation, which can lead to undesirable flavors. Microencapsulation technology has improved the viability of omega-3 bread products, though such techniques increase production costs (Feizollahi et al., 2018).

2.2.8 Breads fortified with protein

Protein-fortified breads have become popular in athletic and aging populations. These products often use plant-based proteins such as chickpea, soy, or lentil isolates. While they support muscle maintenance and satiety, texture and flavor changes may limit broad consumer appeal (Xing et al., 2021).

2.2.9 Breads fortified with antioxidants

Antioxidant-fortified breads may reduce oxidative stress and lower chronic disease risk. Common additions include polyphenols, vitamin C, and vitamin E. However, antioxidant stability during baking varies significantly. Polyphenols from wholegrain cereals and seeds are more heat-stable than synthetic vitamin C, making them more suitable for fortified bread formulations (Benítez et al., 2018).

2.2.10 Breads fortified with probiotics and prebiotics

These breads promote gut health but present major formulation challenges. Probiotic strains must survive high baking temperatures, which often necessitates post-bake application (e.g., as a filling or coating). Prebiotics such as inulin are more heat-stable and easier to incorporate (Longoria-García et al., 2018). Regional interest is growing, particularly in health-conscious markets.

2.3 Positive effects of fortified breads on consumer health

Fortified breads offer a wide range of health benefits due to the incorporation of essential vitamins, minerals, and bioactive compounds. These benefits extend across various domains of health, including nutritional deficiency prevention, immune support, bone integrity, and chronic disease mitigation. However, the extent of these benefits can vary based on demographic characteristics, dietary habits, and regional public health strategies. Recent longitudinal studies and meta-analyses provide stronger evidence supporting these benefits. For example, a systematic review study demonstrated that regular consumption of folic acid-fortified bread significantly reduced the incidence of neural tube defects and improved folate status in women of reproductive age (Castillo-Lancellotti et al., 2013). Similarly, a randomized controlled trial by Nikooyeh et al. (2016) showed that vitamin D-fortified bread improved serum vitamin D levels comparably to supplements, supporting its use in public health nutrition strategies. The following outlines the key benefits associated with the consumption of fortified breads:

2.3.1 Prevention of nutritional deficiencies

Iron, folic acid, vitamin D, and zinc are commonly added to bread formulations to address prevalent deficiencies. According to Diego Quintaes et al. (2017) iron-fortified bread can reduce anemia prevalence (30%) in pregnant women and children. However, effectiveness varies by region; for instance, areas with low baseline anemia rates may see less pronounced impacts. Moreover, socioeconomic barriers may limit access to fortified products, especially in rural or underserved communities (Diego Quintaes et al., 2017). Contrast high-adoption countries (e.g., U.S. folic acid mandate) with low-resource settings where distribution challenges persist (Horton & Mannar, 2018).

2.3.2 Immune system support

Vitamins C and D, zinc, and selenium are essential for immune function. Observational, cross-sectional study in the UK (Redfern et al., 2022) found that individuals with higher intake of fortified foods had lower incidence rates of respiratory infections. Zinc-fortified bread, in particular, may be helpful in immune defense during flu seasons or pandemics. Nonetheless, variability in nutrient absorption and interactions with medications can influence individual

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responses. Additionally, minerals like zinc and selenium, which are often added to fortified breads, boost the immune system. These elements support white blood cell production and overall immune system performance, thereby reducing the risk of chronic illnesses and infections (Korzeniowska et al., 2017). Regular consumption of such breads is especially beneficial for vulnerable groups such as children and the elderly.

2.3.3 Improvement of bone health

Fortified breads containing calcium and vitamin D are essential for maintaining bone health and preventing conditions such as osteoporosis and rickets. These nutrients increase bone density and reduce the risk of fractures. In both developing and developed countries, deficiencies in nutrients such as iron, calcium, iodine, and vitamin D are relatively common (Polzonetti et al., 2020).

Calcium and vitamin D fortification help mitigate osteoporosis and rickets. Some studies reported improved bone mineral density in elderly populations consuming calcium-enriched bread regularly (Polzonetti et al., 2020). However, gender and age-specific responses vary, with postmenopausal women and the elderly benefiting more significantly than younger adults. For example, iron-fortified breads help prevent iron-deficiency anemia, while calcium-enriched breads aid in preventing bone-related disorders (Joshi et al., 2024). In populations with limited dairy consumption, calcium-fortified breads can serve as a practical alternative source of this vital nutrient.

2.3.4 Reduction in the prevalence of anemia

Iron deficiency is a leading cause of anemia, particularly among pregnant women and children (Diego Quintaes et al., 2017). The consumption of iron-fortified breads can significantly enhance the body's iron stores and alleviate anemia-related symptoms such as fatigue, weakness, and cognitive difficulties (Diego Quintaes et al., 2017). Numerous studies have confirmed that iron fortification of food products is one of the most effective strategies for reducing the incidence of anemia in populations (Huma et al., 2007; Pachón et al., 2015).

2.3.5 Improvement of digestive function

Breads enriched with dietary fiber contribute to better digestive health. Dietary fibers increase stool bulk and promote regular bowel movements, thereby reducing issues like constipation (Kaczmarczyk et al., 2012). The fibers present in fortified bread aid in improving intestinal motility and maintaining gut health. Moreover, fibers support the balance of the gut microbiome and stimulate the growth of beneficial intestinal bacteria (Kaczmarczyk et al., 2012). The consumption of soluble fibers can also help lower blood cholesterol levels and regulate blood glucose, which is especially advantageous for individuals with type 2 diabetes and cardiovascular diseases.

2.3.6 Weight management and diabetes risk reduction

Fiber-fortified breads enhance gut motility and support microbiome balance. A study by Patel (2015) highlighted the benefits of soluble fiber in regulating blood glucose and promoting satiety, which aids in weight management. However, excessive fiber intake without gradual dietary adjustment may cause gastrointestinal discomfort in some individuals.

2.3.7 Promotion of cardiovascular health

Fortified breads with antioxidants, fiber, and omega-3s have been associated with reduced risk of cardiovascular disease, diabetes, and inflammation-related conditions. According to Alahmari (2024) long-term intake of omega-3-fortified bread may help reduce triglyceride levels and lower systemic inflammation. Omega-3s help lower inflammation, improve blood lipid profiles, and enhance vascular function, thereby decreasing the risk of heart attacks and related conditions. In addition, the dietary fibers in fortified breads assist in reducing low-density lipoprotein (LDL or "bad" cholesterol), increasing high-density lipoprotein (HDL or "good" cholesterol), regulating blood pressure, and ultimately lowering the overall risk of cardiovascular diseases (Alahmari, 2024). However, impacts differ based on lifestyle factors and baseline dietary patterns, highlighting the need for tailored fortification strategies.

2.3.8 Enhancement of cognitive function

Breads fortified with B vitamins, particularly vitamin B12 and folic acid, can enhance cognitive performance and memory (Korzeniowska et al., 2017). These vitamins are effective in synthesizing neurotransmitters and maintaining brain health. A study showed that regular consumption of fortified breads containing these nutrients may help reduce the risk of age-related cognitive decline (Korzeniowska et al., 2017).

2.3.9 Support for child growth and development

Due to their nutritional content, fortified breads can significantly contribute to the growth and development of children (Berner et al., 2014). Iron and folic acid, for instance, are essential for brain development and red blood cell formation. Regular intake of such breads during childhood may improve academic performance and reduce the risk of developmental disorders (Berner et al., 2014).

2.3.10 Weight management and increased satiety

Breads enriched with dietary fiber promote satiety and can assist in weight management (Patel, 2015). Fibers slow down the digestive process, stabilize blood glucose levels, and help prevent overeating. These characteristics make fiber-fortified breads a suitable option for individuals aiming to lose weight or maintain a healthy weight (Patel, 2015).

2.3.11 Prevention of chronic diseases

The antioxidants and essential nutrients found in fortified breads can help prevent chronic diseases such as diabetes, cancer, and cardiovascular disorders. For example, adding antioxidants to bread can reduce oxidative stress and protect cells and DNA from damage (Alahmari, 2024). Moreover, the inclusion of omega-3 fatty acids in fortified breads may lower the risk of developing chronic inflammatory diseases. In summary, due to their wide range of physical and mental health benefits, fortified breads are recognized as an effective strategy in combating malnutrition and improving public health. Their consumption, particularly in developing countries where nutritional deficiencies are widespread, can increase the quality of life (Alahmari, 2024).

2.4 Negative health effects of fortified breads on consumers

While fortified breads have garnered considerable attention for their enhanced nutritional value and positive impact on consumer health, their consumption may also be associated with certain challenges and adverse effects. These effects can arise from various factors such as excessive intake of nutrients, specific sensitivities, or interactions among food components. This section outlines the potential negative health effects of consuming fortified breads.

2.4.1 Risk of micronutrient overconsumption

Excess intake of certain micronutrients from fortified bread, especially when combined with supplements, can lead to toxicity. For instance, chronic excessive iron intake may cause iron overload and increase oxidative stress, particularly in individuals with hereditary hemochromatosis, a genetic disorder affecting 0.3-0.5% of the population. Similarly, consuming more than the tolerable upper intake level (UL) of vitamin D (100 μg/day) may cause hypercalcemia (Abdul Majeed et al., 2025). Regulatory agencies like the European Food Safety Authority (EFSA) and Food and Drug Administration (FDA) set ULs and guide fortification practices to avoid excessive intakes. Food fortification programs must incorporate population-level dietary intake assessments to mitigate this risk.

2.4.2 Allergic reactions and sensitivities

Fortified bread may include allergens such as soy, dairy derivatives, or novel proteins used as nutrient carriers or fortification agents. For example, soy protein isolates used for protein or iron fortification can trigger allergic responses in susceptible individuals. Food allergies affect approximately 1-3% of adults and up to 6-8% of children globally (Gargano et al., 2021). Labeling regulations in most countries require the declaration of allergenic ingredients, and food safety authorities monitor emerging allergen risks associated with fortification compounds.

2.4.3 Changes in organoleptic properties of bread

Nutrient addition-particularly iron or fiber-can cause undesirable sensory changes. For instance, ferrous sulfate imparts a metallic taste and may darken the bread's color. These effects can lower consumer acceptance. To address this, food scientists employ techniques like microencapsulation, coating, or using less-reactive nutrient forms (e.g., ferric pyrophosphate) (Mollakhalili-Meybodi et al., 2023). Consumer sensory trials are vital in regulatory approval processes to ensure that fortified products remain palatable and marketable.

2.4.4 Higher economic costs

Fortified bread generally incurs higher production costs due to nutrient sourcing, formulation complexity, and quality control. These costs are often passed on to consumers, potentially limiting access in low-income settings. According to Horton & Mannar (2018) cost increases range from 5-15% depending on the nutrient mix. Government subsidies, social protection programs, and public-private partnerships are essential to enhance affordability and equitable access.

2.4.5 Nutrient interactions

Simultaneous fortification with multiple nutrients may lead to biochemical interactions that hinder absorption or efficacy. For instance, non-heme iron competes with zinc and calcium for transport pathways in the gut, and excess folic acid can mask vitamin B12 deficiency, delaying diagnosis of neurological damage. This masking effect is particularly concerning in the elderly, where B12 malabsorption is more common. The prevalence of B12 deficiency in older adults ranges from 5% to 20%, depending on diet and region (Iossifidis et al., 2021). Formulation strategies must follow nutrient compatibility charts and align with Codex Alimentarius guidelines to avoid adverse interactions. Table 1 summarizes key nutrient-nutrient interactions commonly encountered in fortified breads. These interactions may influence the bioavailability and efficacy of added micronutrients. Understanding such dynamics is critical for effective formulation and consumer safety.

2.4.6 Digestive issues

While fiber fortification offers many benefits, abrupt increases in fiber intake-especially above 30-40 g/day-can lead to bloating, gas, or constipation in unaccustomed individuals. These effects are transient and usually subside with gradual dietary adaptation (Dwyer et al., 2015). High-fiber fortified breads may lead to discomfort, particularly for individuals unaccustomed to fiber-rich diets. Consumer guidance and proper labeling on fiber content (soluble vs. insoluble) can reduce discomfort and support digestive tolerance.

2.4.7 Potential nutrient degradation during processing

Heat-sensitive vitamins such as vitamin C, thiamine (B1), and riboflavin (B2) may degrade during mixing, fermentation, and baking. Losses can range from 10% to 90%

depending on baking temperature and time (Bredariol & Vanin, 2022). As a result, the actual nutrient content of the bread may be lower than the claimed amount, potentially diminishing the intended nutritional benefits. To ensure nutritional efficacy, overages (adding more than the target amount) and encapsulation technologies are employed. Regulatory authorities require manufacturers to declare the final nutrient content after processing, not the raw mix levels.

2.4.8 Dependency on fortified bread at the expense of a varied diet

Relying heavily on fortified bread can reduce dietary diversity, leading to insufficient intake of phytochemicals, polyphenols, and other unfortified nutrients found in whole fruits, vegetables, legumes, and nuts. This risk is particularly concerning in urban populations with limited food literacy. Public health messaging should emphasize that fortified products are complementary to-not substitutes for-a diverse and balanced diet (Dwyer et al., 2015).

2.4.9 Adverse effects on specific population groups

Certain population groups, such as infants, the elderly, or individuals with chronic kidney disease, may face heightened sensitivity to high levels of certain nutrients. For example, excessive calcium or vitamin D may lead to hypercalcemia in elderly individuals with impaired renal function. Infants under six months may be susceptible to nutrient imbalances if fed with highly fortified products (Vandevijvere et al., 2012). Population-specific intake guidelines and professional dietary guidance are necessary to avoid unintended harm.

2.4.10 Food safety and processing concerns

The inclusion of synthetic additives or non-traditional fortifying agents raises concerns about food additive safety and long-term exposure effects. Inadequate regulation or quality control can result in inconsistent dosing, contamination, or instability (Marone, 2016). To safeguard public health, most countries require Good Manufacturing Practices (GMP), Hazard Analysis and Critical Control Points (HACCP), and regular compliance audits for fortified food manufacturers. Although the risks associated with fortified breads are generally low in the context of regulated production and responsible consumption, they warrant close attention. Integration of risk management strategies, regulatory oversight, and public education can help maximize benefits while minimizing harm. Tailored fortification programs, aligned with local dietary needs and monitored for efficacy and safety, are essential to ensure that fortified bread contributes positively to public health.

Table 1. Summary of Nutrient Interactions in Fortified Breads

Nutrient 1	Nutrient 2	Type of Interaction	Effect/Mechanism	Potential Mitigation Strategy	Reference
Iron (non-heme)	Zinc	Competitive absorption	Competes for DMT1 transporter in the gut; high iron can inhibit zinc uptake.	Use chelated zinc (e.g., zinc gluconate); stagger dosing.	(Dwyer et al., 2015)
Iron	Calcium	Competitive absorption	Calcium inhibits both heme and non-heme iron absorption	Avoid co-fortifying with high doses; adjust formulation	(Dwyer et al., 2015)
Folic Acid	Vitamin B12	Masking effect	High folic acid intake can mask symptoms of B12 deficiency, delaying diagnosis.	Screen high-risk groups (elderly); monitor B12 status	(Crider et al., 2011)
Calcium	Magnesium	Competitive uptake	Excess calcium can reduce magnesium absorption	Maintain balanced ratios; dietary diversification	(Joshi et al., 2024)
Iron	Vitamin C	Synergistic absorption	Vitamin C reduces ferric to ferrous iron, enhancing non-heme iron absorption.	Co-fortify iron with vitamin C	(Piskin et al., 2022)
Zinc	Copper	Competitive absorption	Excess zinc may inhibit copper absorption	Maintain appropriate Zn: Cu ratio (~8:1)	(Dwyer et al., 2015)
Fiber	Iron, Zinc, Calcium	Inhibitory binding	Phytates and fiber bind minerals, reducing bioavailability	Use low-phytate flour; enzyme treatment	(Alina et al., 2019)
Vitamin D	Calcium	Synergistic effect	Vitamin D promotes calcium absorption in the intestine	Common co-fortification strategy	(Nikooyeh et al., 2016)
Omega-3s	Iron, Oxygen	Oxidation risk	Polyunsaturated fats can oxidize in the presence of iron, reducing nutritional value.	Use antioxidants; microencapsulation	(Feizollahi et al., 2018)

2.5 Challenges and considerations in the production of fortified bread

While the production of fortified bread is recognized as a cost-effective strategy for improving public nutrition, it involves several complex challenges. These range from technical issues such as nutrient degradation and sensory changes, to economic and sociocultural barriers like production costs and consumer acceptance. Addressing these issues requires not only technical innovation but also regulatory support and public engagement. This section explores these challenges in depth and highlights successful interventions and technologies that can mitigate them.

2.5.1 Selection of appropriate nutrients for fortification

One of the primary challenges in producing fortified bread is determining the type and amount of nutrients to be added. Choosing nutrients suitable for fortification depends on their compatibility with baking processes and their stability under heat, pH, and oxidation. For instance, microencapsulated iron has been used to reduce reactivity and minimize sensory changes. A study by Zimmermann & Windhab (2009) demonstrated that lipid-based encapsulation of ferrous fumarate preserved iron bioavailability while preventing metallic taste and color change in bread. For instance, water-soluble vitamins such as vitamin C are highly susceptible to degradation at high temperatures and may not remain in the final product in effective amounts (Dwyer et al., 2015).

2.5.2 Nutrient stability throughout the production process

Bread production involves multiple stages, including mixing, fermentation, and baking, all of which can negatively affect the stability and efficacy of added nutrients (Cappelli & Cini, 2021). Thermal degradation of vitamins like B1, B2, and D during baking can significantly reduce the nutritional value of the final product. To address this, encapsulation in hydrocolloids or polysaccharide matrices has been used to shield vitamins during baking. For example, Nikooyeh et al. (2016) demonstrated the effectiveness of vitamin D3 microencapsulated in starch-lipid carriers, achieving over 80% retention post-baking. This approach also reduces nutrient interaction and ensures uniform distribution.

2.5.3 Alteration of sensory and organoleptic properties

Sensory acceptance is crucial for consumer uptake. Iron fortification, for example, can cause undesirable changes in taste and color. Successful formulations have used ferric pyrophosphate and microencapsulated iron salts to eliminate metallic aftertaste (Dwyer et al., 2015). In the case of fiber-fortified breads**,** blending soluble (e.g., inulin) and insoluble fibers in optimized ratios has been shown to preserve softness and reduce density, improving texture and mouthfeel (Almoumen et al., 2025).

2.5.4 Increased production Costs

Fortified bread production involves added costs for high-grade nutrients, processing technologies, and quality assurance (Horton & Mannar, 2018). However, cost-benefit analyses from countries like Chile and Australia show significant long-term savings. For example, Australia's mandatory folic acid fortification was estimated to save AUD 61 million annually by reducing neural tube defects (Saing et al., 2019). Governments can subsidize fortification ingredients or provide tax incentives to manufacturers to offset initial investments.

2.5.5 Regulatory and standardization challenges

Compliance with fortification standards-such as Codex Alimentarius or national food safety guidelines-requires accurate labeling, batch testing, and nutrient monitoring. The U.S. and Canada use reference dietary intakes (RDIs) to guide fortification levels and mandate regular audits (Murphy et al., 2016). Adopting digital traceability systems (e.g., blockchain-based records) in production has been proposed to enhance regulatory compliance and consumer trust (Shegelman et al., 2019).

2.5.6 Cultural factors and consumer preferences

Sensory and cultural expectations of bread vary globally. In regions where white, soft-textured bread is preferred, high-fiber or protein additions may be rejected (El Hoss et al., 2024). To improve acceptance, targeted social marketing campaigns (e.g., in Lebanon and Iran) have emphasized fortified bread's health benefits for children and pregnant women, increasing public buy-in (Mohammadi-Nasrabadi et al., 2023). Participatory product development, involving local consumers in sensory trials, has also led to higher adoption rates.

2.5.7 Nutrient interactions

Complex interactions (e.g., iron inhibiting zinc absorption) can reduce efficacy. Successful programs address this by staggering fortification-fortifying different products with complementary nutrients-or using chelated mineral forms (e.g., zinc gluconate) that resist interference. For instance, iron and calcium can compete for absorption in the gastrointestinal tract (Dwyer et al., 2015). WHO recommends using bioavailability enhancers, like vitamin C with iron, to improve absorption in formulations (Piskin et al., 2022).

2.5.8 Technical limitations in industrial-scale production

Ensuring homogeneity in nutrient distribution and controlling dosages across batches require precision blending machines and automated dosing systems. The use of advanced equipment is often required to control nutrient dosage and maintain product consistency, which increases both the complexity and cost of production. For example, bread factories in Brazil and India have adopted pre-mix blending stations that ensure even micronutrient dispersion (Soliman et al., 2012). Pilot-scale studies have shown that such equipment reduces nutrient variance by up to 95% compared to manual mixing (Cappelli & Cini, 2021).

2.5.9 Education and awareness-raising

An essential consideration in the production of fortified bread is the education of both consumers and producers. Consumer education campaigns have proven vital in boosting fortified bread uptake. Similarly, producers must be equipped with sufficient knowledge regarding fortification techniques, nutrient selection, and quality control to ensure product effectiveness and safety. In South Africa, for instance, fortification logos and nutrition education in schools led to a 20% increase in consumer trust and product demand (Oldewage-Theron & Egal, 2012). Manufacturers and health ministries should collaborate on multimedia public health campaigns, community demonstrations, and clear on-pack labeling (e.g., “with added iron to reduce fatigue”) (Mesta-Corral et al., 2024).

2.5.10 Monitoring effectiveness and impact assessment

A critical challenge is evaluating the effectiveness of fortified bread in improving public health (Abdul Majeed et al., 2025). This requires comprehensive studies to assess its role in reducing nutritional deficiencies and promoting better health outcomes. Moreover, continuous monitoring of product quality and safety is necessary to ensure that nutritional goals are being met. In conclusion, while the production of fortified bread presents a promising solution to combat nutritional deficiencies in various populations, it also entails numerous technical, economic, and social challenges. Long-term impact assessment requires biomarker studies, dietary surveys, and epidemiological data. Governments in countries like the USA, Chile, and Iran monitor serum folate, hemoglobin, and vitamin D levels in population subgroups through health surveillance systems (Mohammadi-Nasrabadi et al., 2023). Success in this field depends on careful planning, the application of advanced technologies, adherence to regulatory standards, and broad-based educational efforts (Dwyer et al., 2015). Collaborations between universities, health agencies, and industry can support robust data collection and program evaluation.

4. Conclusion

Bread, as one of the most widely consumed foods globally, presents a valuable platform for improving public health through nutrient fortification. This review has shown that fortified bread can play a crucial role in addressing key nutritional deficiencies-such as iron-deficiency anemia, vitamin D deficiency, and inadequate fiber intake-especially in vulnerable groups like children, pregnant women, and the elderly. Fortification can also contribute to preventing chronic diseases such as osteoporosis, cardiovascular disorders, and type 2 diabetes. However, the long-term success of fortified bread initiatives depends on overcoming significant production, sensory, economic, and policy challenges. These include ensuring nutrient stability during baking, maintaining consumer-acceptable taste and texture, minimizing costs, and navigating complex regulatory landscapes.

Future research should focus on: 1- Longitudinal studies to evaluate the clinical effectiveness of fortified bread in reducing micronutrient deficiencies over time. 2- Investigating bioavailability and nutrient interactions in real-world consumption scenarios. 3- Evaluating consumer behavior and acceptability across different regions and demographics.

Policy recommendations include: 1- Implementing government subsidies to reduce production costs and increase access to fortified breads in low-income areas. 2- Launching public awareness campaigns to educate consumers on the health benefits of fortified bread, similar to the successful folic acid campaigns in the U.S. and Australia. 3- Mandating fortification of staple flours with essential nutrients in regions with high deficiency prevalence, accompanied by strong quality assurance systems.

Fortified bread should also be integrated into broader food security and nutrition strategies, such as school meal programs, maternal and child health initiatives, and national dietary guidelines. For instance, South Africa’s use of school-based nutrition education and on-pack fortification logos has improved consumer trust and uptake of fortified foods.

Lastly, a multisectoral approach involving government agencies, food manufacturers, public health experts, and local communities is essential. Countries like Iran and Chile have demonstrated that partnerships between ministries of health, academia, and the private sector can ensure product safety, compliance, and population-level impact.

In conclusion, fortified bread is a practical, scalable, and sustainable solution for improving nutritional health and addressing global malnutrition. Aligning technological innovation with evidence-based policy and community engagement can significantly enhance health outcomes and food system resilience.

Authors’ Contributions

Maryam Hassani: Conceptualization; Data curation; Investigation; Writing original draft; Writing-review & editing. **Hassan Hassanzadazar:** Conceptualization; Writing-review & editing. **Esrafil Asgari:** Supervision; Conceptualization; Visualization; Writing-review & editing. **Hossein Arabzade:** Investigation; Visualization. **Nastaran Noori:** Investigation; Writing-original draft.

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Conflicts of Interest

The authors have declared no competing interests.

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Ethical Considerations

The article is extracted from the project with the ethics code of IR.ZUMS.BLC.1403.144.

Using Artificial Intelligence

No type of artificial intelligence was used.

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