

Food Fortification for Improving Micronutrient Status and Overall Nutritional Health: A Comprehensive Review

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Keywords: Food fortification, micronutrient deficiency, biofortification, public health.

Received on 25 Jan 2026

Accepted on 28 Feb 2026

Published on 10 Mar 2026

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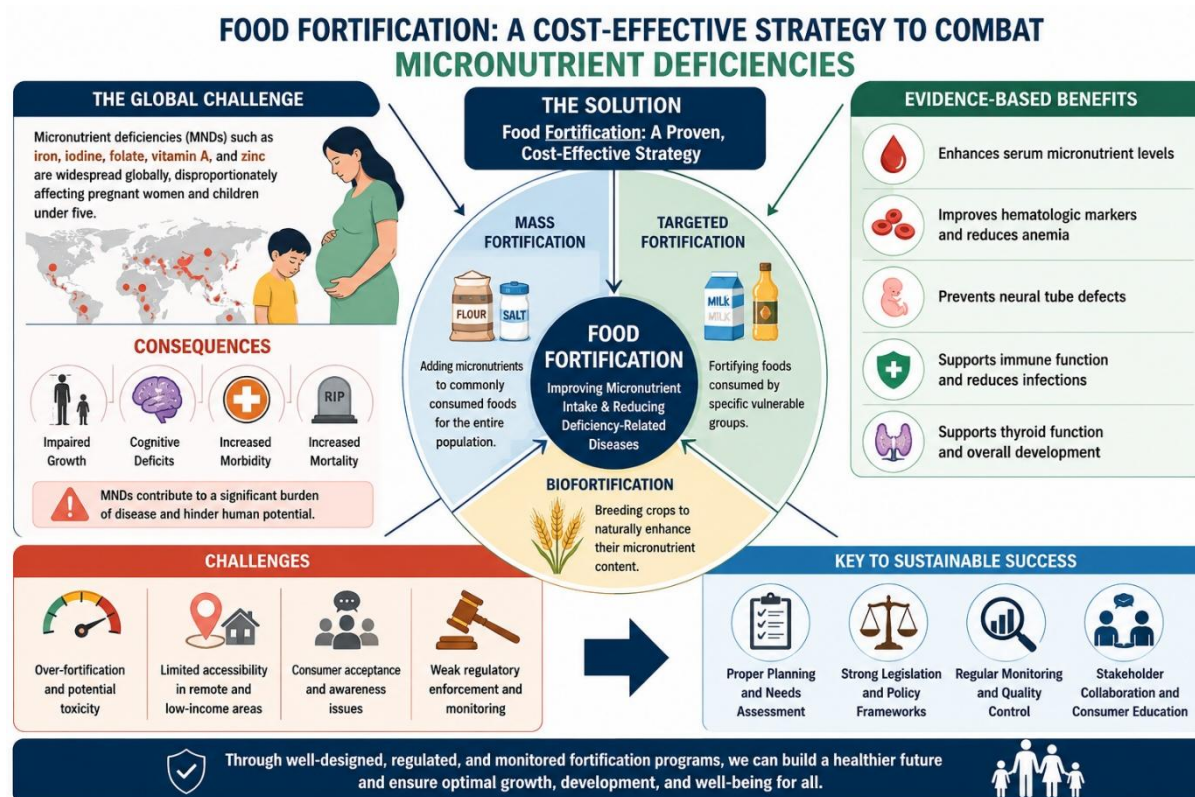
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Abstract

Micronutrient deficiencies (MNDs) such as iron, iodine, folate, vitamin A, and zinc are widespread globally, disproportionately affecting pregnant women and children under five. These deficiencies contribute to impaired growth, cognitive deficits, and increased morbidity and mortality. Food fortification, including mass fortification, targeted fortification, and biofortification, has emerged as a cost-effective strategy to improve micronutrient intake and reduce deficiency-related diseases. Evidence shows fortified foods enhance serum micronutrient levels, improve hematologic markers, reduce anemia, prevent neural tube defects, and support immune and thyroid functions. Despite clear benefits, challenges exist such as over-fortification, accessibility, consumer acceptance, and regulatory enforcement. Proper planning, legislation, and monitoring are essential for the sustainable success of fortification programs.

Graphical Abstract



Introduction

Micronutrients are essential to sustain life and for optimal physiological function. Widespread global micronutrient deficiencies (MNDs) exist, with pregnant women and their children under 5 years at the highest risk. Iron, iodine, folate, vitamin A, and zinc deficiencies are the most widespread MNDs, and all these MNDs are common

contributors to poor growth, intellectual impairments, perinatal complications, and increased risk of morbidity and mortality[1]. Iron deficiency is the most common MND worldwide and leads to microcytic anemia, decreased capacity for work, as well as impaired immune and endocrine function. Iodine deficiency disorder is also widespread and results in goiter, mental retardation, or reduced cognitive function. Adequate zinc is necessary for optimal immune function, and deficiency is associated with an increased incidence of diarrhea and acute respiratory infections, major causes of death in those <5 years of age. Folic acid taken in early pregnancy can prevent neural tube defects. Folate is essential for DNA synthesis and repair, and deficiency results in macrocytic anemia. Vitamin A deficiency is the leading cause of blindness worldwide and also impairs immune function and cell differentiation. Single MNDs rarely occur alone; often, multiple MNDs coexist. The long-term consequences of MNDs are not only seen at the individual level but also have deleterious impacts on economic development and human capital at the country level. Perhaps of greatest concern is the cycle of MNDs that persists over generations and the intergenerational consequences of MNDs that we are only beginning to understand[2]. Prevention of MNDs is critical and traditionally has been accomplished through supplementation, fortification, and food-based approaches including diversification. It is widely accepted that intervention in the first 1,000 days is critical to break the cycle of malnutrition; however, a coordinated, sustainable commitment to scaling up nutrition at the global level is still needed. Understanding the epidemiology of MNDs is critical to understand what intervention strategies will work best under different conditions[3].

Hidden Hunger

Hidden hunger, or micronutrient deficiency, is when someone lacks essential vitamins and minerals (like iron, zinc, vitamin A) for proper body function, even if they eat enough calories, leading to unnoticed health issues like poor growth, weakened immunity, and chronic disease risk, affecting billions globally and present in both developing and developed nations due to poor diet quality[4].

What Is Food Fortification

Fortification is the process of adding nutrients or non-nutrient bioactive components to edible products (e.g., food, food constituents, or supplements). Fortification can be used to correct or prevent widespread nutrient intake shortfalls and associated deficiencies, to balance the total nutrient profile of a diet, to restore nutrients lost in processing, or to appeal to consumers looking to supplement their diet[5]. Food fortification could be considered as a public health strategy to enhance nutrient intakes of a population. Over the past century, fortification has been effective at reducing the risk of nutrient deficiency diseases such as beriberi, goiter, pellagra, and rickets. However, the world today is very different from when fortification emerged in the 1920s. Although early fortification programs were designed to eliminate deficiency diseases, current fortification programs are based on low dietary intakes rather than a diagnosable condition[6].

Types of Fortification

Mass Fortification

Large-scale food fortification (LSFF) refers to the process whereby one or more essential micronutrients are deliberately added to a staple food or condiment during processing in order to improve its nutritional quality. Otherwise referred to as mass fortification, it is a nutrition-specific intervention that is typically initiated, mandated, and regulated by governments for the purpose of correcting or avoiding micronutrient deficiencies in populations that are at increased risk[34]. Basic commodities, such as flour, oil, salt, sugars, and condiments, are typically chosen as the vehicle for LSFF due to their widespread and regular consumption. Fortificants are defined as the source of micronutrient, while micronutrient premixes refer to that which is blended with the fortificant in order to more feasibly introduce the mixture into the food vehicle[7]. Numerous factors must be taken into consideration throughout planning, including the

concentration of the fortificant – such that it is both efficacious and safe its absorptive properties, stability, and how it will affect the sensory qualities of the food vehicle chosen. LSFF is currently promoted as a cost-effective strategy for reducing physiological and clinical outcomes associated with micronutrient deficiencies, particularly when food is processed centrally and existing technologies and distribution networks can be taken advantage of[33]. This is in contrast to targeted fortification practices that capitalize on specific food vehicles for a particular subset of the population (e.g., infant formula) or home fortification, whereby soluble or crushable tablets, micronutrient powders, or micronutrient-rich spreads are added to foods at the level of the household. Supplementation, usually in the form of pills, capsules, and syrups, is another public health intervention aimed at reducing micronutrient deficiencies[8].

Targeted Fortification

Targeted fortification aims to improve the nutritional status of specific high-risk groups, such as pregnant women, infants, and individuals with specific medical conditions. This method is particularly useful in addressing deficiencies in vulnerable populations who may not benefit from mass fortification[9]. One approach to targeted fortification is the development of specialized food products such as ready-to-use therapeutic foods (RUTF) and complementary foods for infants[32]. These products are often fortified with multiple micronutrients, including iron, zinc, vitamin A, and folic acid, to support growth and immune function. Additionally, biofortification, a form of targeted fortification, involves breeding crops with higher micronutrient content to enhance their nutritional value[10]. For example, biofortified rice with increased iron and zinc, and vitamin A-rich golden rice, have been developed to address deficiencies in populations relying heavily on rice-based diets. Targeted fortification is highly effective in reducing deficiencies in specific groups, but it requires strong distribution systems and consumer education to ensure proper utilization. (Show in figure 1)



Figure 1: Commonly fortified foods such as oil, flour, and salt used to reduce micronutrient deficiencies

Biofortification

The WHO defines biofortification as “the practice of deliberately increasing the content of an essential micronutrient, that is, vitamins and minerals (including trace elements) in a food crop through agronomic practices, conventional plant breeding, or modern biotechnology, so as to improve the nutritional quality of the food supply and provide a public health benefit with minimal risk to health” (WHO, 2019)[11]. Bio-fortification is a sustainable and cost-effective approach that enhances the nutrient content of crops through conventional breeding or genetic modification. This method is particularly beneficial for populations in rural areas with limited access to industrially fortified

foods[31]. Genetically modified rice enriched with beta-carotene to combat vitamin A deficiency[12]. Additionally, zinc-fortified wheat has been designed to improve immune function and growth. Furthermore, bio-fortified crops such as iron-rich beans, and orange-fleshed sweet potatoes (rich in vitamin A) have shown significant potential in reducing micronutrient deficiencies[13]. Bio-fortification offers sustainability, as nutrients are embedded in the plant itself and it could be prove beneficial for rural populations with limited access to fortified foods. While bio-fortification offers long-term benefits, challenges include consumer acceptance, regulatory approval, and the need for largescale adoption by farmers[14].

Fortification Strategy to Reduce Micronutrient Deficiency

Food fortification has lowered the incidence of micronutrient deficiencies (MNDs) that were previously common, and has improved the health status (and also other key indicators, such as economic and educational status) of a large proportion of the population(s) involved[15]. In 2002 the World Health Report identified iodine, iron, vitamin A, and zinc deficiencies as being among the world's most serious health risk factors[30]. The four key strategies identified to address MNDs are: dietary improvement, supplementation, food fortification, and global public health measures[16]. Short-term strategies such as nutrient supplementation have been effective in providing immediate relief in several countries, but this approach was not sustainable in the long term. The World Bank, WHO, UNICEF, Micronutrient Initiative (MI) and Global Alliance for Improved Nutrition (GAIN) have identified fortification as one of the most costeffective health interventions. Fortification of staple foods with micronutrients is currently gaining momentum in many developing countries[17].

Fortification of Specific Foods

Milk products: Milk is fortified with minerals such as Ca, Fe, Zn, Se. The dairy industry benefits from fortified products that are appealing and healthy. Careful preparation ensures nutritional value while maintaining taste[18].

Flour: Nutrients in powdered form can be mixed easily. Fortification of rice flour with iron, zinc, and folate improved absorption in preschool children and enhanced growth[29].

Salt: Salt is universally consumed, making it an effective vehicle. Fortification with iodine and folic acid improves urinary iodine levels and prevents neural tube defects[19].

Micronutrients and Their Impact on Human Health

Micronutrients, including vitamins and minerals, are essential for maintaining human health, supporting physiological functions, and preventing diseases. They play critical roles in immune function, brain development, metabolism, and overall well-being[20]. Deficiencies can lead to serious health complications, while adequate intake ensures optimal growth and longevity[21]. Vitamins A, C, D, and E, along with minerals like zinc and selenium, enhance immune responses. Folic acid prevents neural tube defects, and iron supports cognitive development. Calcium, vitamin D, magnesium, and phosphorus maintain bone health. B-complex vitamins are crucial for energy metabolism[28].

How Fortified Foods Improve Human Health Increased Micronutrient Status: Fortified foods significantly increase serum micronutrient concentrations and improve hematologic markers[22].

Reduction in Anemia and Iron Deficiency: Iron-fortified foods raise hemoglobin and ferritin levels, reducing anemia.

Prevention of Congenital Defects: Folic acid fortification prevents neural tube defects in newborns.

Improved Iodine Status[27]: Iodine fortification enhances thyroid function.

Enhanced Serum Vitamin Levels: Vitamin A and D fortification improves immune function and bone health.

Public Health Outcomes: Population-level fortification reduces disease burden from deficiencies[23].

General Principles of Food Fortification and Quality Control FAO and Codex Alimentarius guidelines provide international standards. Legislation ensures micronutrient levels are safe and effective. Proper planning and

monitoring are essential for program success. Advantages and Limitations of Food Fortification.(Show in figure 2)



Figure 2: Key strategies to address micronutrient deficiencies, including supplementation, fortification, and dietary diversification.

Advantages:

Does not require dietary changes
Delivers continuous nutrient intake
Benefits children and women
Sustainable over time[24].

Limitations:

Accessibility issues
Severe deficiencies may require supplementation
Infections may limit effectiveness
Safety, technological, and cost constraints[25].

Current Challenges and Regulatory Issues

Risks include over-fortification, ethical concerns, industry influence, and consumer acceptance. Monitoring and transparent policies are critical to prevent toxicity and ensure public health benefits[26].

Conclusion

Food fortification is a proven, cost-effective public health strategy to reduce micronutrient deficiencies, improve health outcomes, and enhance human capital. Sustainable programs require careful planning, regulatory oversight, consumer education, and monitoring to maximize benefits while minimizing risks. Mass fortification, targeted fortification, and bio-fortification collectively provide comprehensive solutions to address global micronutrient deficiencies.

Future Perspectives

Future food fortification strategies are expected to evolve beyond conventional population-based interventions toward precision nutrition approaches that integrate nutrigenomics, artificial intelligence (AI), and personalized dietary recommendations. AI-driven predictive models may enable the development of individualized fortification strategies based on genetic variability, metabolic status, and dietary patterns, thereby improving micronutrient bioavailability and reducing the risk of both deficiency and excessive intake [35, 43, 55, 65].

The integration of machine learning, precision fermentation, and digital food technologies is anticipated to transform the design of fortified foods. AI can optimize ingredient selection, predict nutrient stability during processing, improve quality assurance, and support the formulation of personalized functional foods with enhanced nutritional value. Emerging precision fermentation technologies may also facilitate sustainable production of vitamins, bioactive peptides, and other health-promoting compounds for future fortification programmes [39, 51, 57, 61, 66].

Future research should increasingly focus on sustainable food systems by utilizing agricultural by-products and novel protein sources as fortification vehicles. Whey proteins, soy proteins, plant proteins, probiotic cultures, and fruit-derived polyphenols

represent promising functional ingredients capable of improving nutritional quality while simultaneously reducing environmental waste and supporting circular bioeconomy initiatives [35, 36, 37, 38, 40, 56, 57, 71, 72, 74].

Rapid advances in nutrigenomics and epigenetics suggest that future fortified foods may not only correct micronutrient deficiencies but also regulate gene expression, DNA methylation, oxidative stress, inflammation, insulin sensitivity, and metabolic health. Such approaches could expand the role of food fortification in preventing obesity, diabetes mellitus, cardiovascular diseases, and other chronic non-communicable disorders [44, 45, 54, 62, 73].

Biofortification is also expected to benefit substantially from genome-editing technologies such as CRISPR and advanced plant breeding. Future staple crops with enhanced concentrations of iron, zinc, folate, provitamin A, and other essential micronutrients may contribute to long-term food security while improving resilience to climate change and environmental stress [46, 47, 68, 74].

Increasing evidence demonstrates that the gut microbiome plays an essential role in micronutrient metabolism and host health. Future fortification strategies are therefore likely to combine micronutrients with probiotics, prebiotics, postbiotics, and microbiome-modulating functional foods to improve nutrient absorption, immune function, and chronic inflammation while promoting overall metabolic health [36, 42, 73].

Novel food-processing technologies—including ultrasonication, controlled fermentation, enzymatic modification, and encapsulation—are expected to enhance nutrient stability, bioaccessibility, sensory quality, and shelf life of fortified products. These innovations may significantly improve the effectiveness and consumer acceptance of next-generation fortified foods [40, 57, 72].

Future public health programmes should also strengthen regulatory frameworks, quality assurance systems, digital monitoring, and evidence-based surveillance to ensure safe implementation of food fortification initiatives. The incorporation of AI-assisted monitoring systems and data-driven policy development could improve programme evaluation, regulatory compliance, and equitable distribution of fortified foods among vulnerable populations [43, 60, 63, 64, 65, 66].

Finally, interdisciplinary collaboration among food scientists, nutritionists, microbiologists, clinicians, agricultural researchers, policymakers, and data scientists will be essential to develop sustainable, affordable, and scientifically validated fortification programmes capable of addressing hidden hunger worldwide. Future translational research integrating food science, biotechnology, public health, and digital technologies will further strengthen the contribution of food fortification toward achieving global nutrition and Sustainable Development Goals [41, 48, 49, 50, 52, 53, 58, 59, 67, 69, 70].

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