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Solving Hidden Hunger: An Integrated Framework for Nutritional Enhancement Across the Food Chain, from Farm to Fork

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Abstract. Hidden hunger (micronutrient deficiency) is a global public health challenge rooted in the systemic loss of nutrients within the modern food system. This paper proposes an integrated "Nutrition Chain Repair" framework aimed at rebuilding nutritional integrity from production to consumption through synergistic multi-node interventions. Based on a systematic review of 11 recent publications (2024-2025), this study identifies three key intervention nodes: At the production end, enhancing the nutritional baseline through biofortification and the development of novel resources (e.g., algal protein). In processing and delivery, applying advanced encapsulation technologies (e.g., liposomes), optimizing traditional processes (e.g., freezing), and utilizing fermentation to protect and deliver nutrients precisely. At the assessment and cognition level, there is an urgent need to reform protein evaluation standards and establish the food matrix as a core paradigm. Flavor perception is the critical bridge ensuring consumer acceptance of technological outcomes and the realization of public health benefits. This study argues that only through such cross-chain, systemic, and synergistic repair can a truly nutrition-sensitive and sustainable food system be built to eradicate hidden hunger.

Keywords: Hidden Hunger, Food System, Biofortification, Nutrient Delivery, Sustainable Nutrition

1. Introduction

Hidden hunger, defined as sufficient energy intake but a deficiency in essential micronutrients, affects over two billion people worldwide and is a major obstacle to achieving Sustainable Development Goal (SDG) 2 [1]. Its cause is not a lack of food quantity, but rather the systemic depletion and loss of nutrients along the "farm-to-fork" chain due to modern intensive agriculture and food processing systems [1]. Despite significant progress in areas like crop breeding, food engineering, and nutrition science, existing solutions remain fragmented, lacking an integrated theoretical framework and practical pathway to diagnose and repair nutrition loss across the entire chain [2]. This study aims to fill this gap by proposing, for the first time, the "Nutrition Chain Repair" framework. Its core thesis is that hidden hunger is the inevitable result of continuous, compounded functional breaks at three critical nodes of the food system: the production source, the

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processing and distribution pipeline, and the assessment and cognition system. Therefore, effective intervention must involve targeted, synergistic systemic repair of these nodes. Through a systematic review of cutting-edge evidence from 2024-2025, this paper constructs and argues for this framework, intending to provide an academically rigorous and practically actionable blueprint for interdisciplinary research, industrial innovation, and public policy.

2. Repair at the production source: nutritional enhancement and resource expansion

Nutritional depletion in food begins at its biological origin. Yield-oriented agricultural paradigms have led to a general decline in the nutrient density of crops, known as the "dilution effect" [1]. Repairing this node requires a two-pronged approach: endogenous enhancement and exogenous resource expansion.

2.1. Biofortification: the strategy of endogenous nutritional improvement

Biofortification uses breeding techniques to increase the content of specific micronutrients in the edible parts of crops, offering a sustainable, food-based solution for improving the nutritional status of target populations [3]. Compared to post-harvest fortification, its advantages lie in the continuity and embeddedness of its benefits; once a variety is adopted, nutritional gains are realized with each harvest without requiring changes in consumer behavior. Integrating biofortification into national agricultural and nutrition security strategies represents a fundamental "genetic coding" repair of the food production system.

2.2. Expanding resource boundaries: developing future foods and recycling by-products

Addressing nutritional challenges requires breaking the resource boundaries of traditional agriculture. Microalgae and macroalgae, with their excellent nutritional profiles (e.g., complete protein, ω-3 fatty acids, vitamins) and extremely low environmental footprint, are regarded as one of the most promising sustainable "future food" resources [4]. Simultaneously, embracing the circular economy concept, the high-value utilization of by-products from existing food chains is crucial. Seafood processing by-products are rich in protein, bioactive peptides, and minerals but are often discarded [5]. Transforming them into high-value nutritional ingredients through modern biotechnology achieves the dual goals of environmental relief and nutritional supplementation.

3. Repair in the processing and delivery link: nutrient protection and precision targeting

Processing, storage, and transportation are major risk points for nutrient loss, but through technological innovation, they can be transformed into key links for nutrient protection and value addition.

3.1. Process optimization: engineering controls to minimize nutrient loss

Conventional unit operations (e.g., thermal treatment, drying, freezing), if not properly controlled, can damage nutrients through pathways like thermal degradation, oxidation, and physical loss. Taking meat freezing as an example, slow freezing leads to the formation of large ice crystals that damage cell structure, causing irreversible drip loss and the loss of water-soluble vitamins, minerals, and proteins [6]. Evidence indicates that implementing rapid deep-freezing, maintaining stable frozen storage temperatures, and employing appropriate thawing methods can significantly reduce

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such quality and nutritional deterioration [6]. This exemplifies the "defensive" repair approach through precise engineering control.

3.2. Advanced delivery systems: enhancing nutrient stability and bioavailability

Many bioactive components (e.g., polyunsaturated fatty acids, probiotics, and polyphenols) are sensitive to processing and gastrointestinal environments and have low bioavailability. Liposomal encapsulation technology provides a revolutionary solution [7]. Liposomes, as nanoscale vesicles composed of phospholipid bilayers, can encapsulate hydrophilic/hydrophobic components in different compartments, forming a physical barrier. This significantly improves the stability of the encapsulated substances and enables their controlled or targeted release in the gastrointestinal tract, greatly enhancing the precision and efficiency of nutritional interventions.

3.3. Biotransformation: fermentation-driven nutrition and function upgrade

Fermentation is an ancient wisdom that utilizes microbial metabolism for the pre-digestion and transformation of food [8]. This process yields multiple benefits: degrading anti-nutrients like phytic acid, improving mineral bioavailability, synthesizing B vitamins, partially degrading macromolecules to increase digestibility, and producing probiotics and various beneficial metabolites (e.g., short-chain fatty acids). Therefore, fermentation is an efficient repair process that "upgrades" food nutrition and function through biotransformation.

4. Repair of the assessment and cognition system: data innovation and paradigm shift

If the benchmarks for assessing nutrition are inaccurate or the cognitive framework is flawed, all upstream repairs may be misdirected. Updating assessment tools and cognitive paradigms is the foundation for ensuring the system evolves toward the correct goals.

4.1. Repairing the data foundation: towards accurate protein assessment

The widely used generic conversion factor ($N \times 6.25$) for calculating "crude protein" seriously ignores differences in amino acid composition and the presence of non-protein nitrogen, leading to systematic data distortion, especially for plant proteins [2]. This directly affects the accuracy of dietary assessment, the truthfulness of food labeling, and the scientific basis of nutrition policies. Repairing this fundamental flaw necessitates a transition towards using food-specific conversion factors or direct determination methods based on amino acid analysis, a prerequisite for achieving precision nutrition.

4.2. Cognitive paradigm shift: from nutritional reductionism to a food matrix systems view

The "nutritionism" perspective, which reduces food to the sum of its nutrients, cannot explain complex diet-health relationships. Food matrix theory posits that the physical structure (matrix) of food governs the release, absorption, and subsequent metabolic kinetics of nutrients, thereby determining its final health effects [9]. For example, the metabolic responses to whole nuts versus nut butter, or whole fruits versus fruit juice, differ significantly. Therefore, nutritional science must shift its focus from isolated chemical components to understanding whole food as a "nutrient delivery system." This is the core theoretical basis for designing healthier foods.

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4.3. Empowering process monitoring: non-destructive analysis with Magnetic Resonance technology

Implementing precise repair requires advanced process monitoring tools. Magnetic Resonance (MR) technology provides powerful, rapid, and non-destructive analytical means [10]. It can be used for quantitative component analysis, microstructure visualization, authenticity identification, and real-time monitoring of dynamic changes during processing and storage. Integrating such technology at critical control points enables "visible" quality control from raw materials to finished products, providing data support for process optimization and nutritional quality assurance.

5. Sensory acceptability: the bridge between technical repair and consumer behavior

The ultimate success of any nutritional intervention depends on its long-term adoption by consumers. Flavor perception (taste, smell, and mouthfeel) is the core sensory driver of food choice and an indispensable bridge connecting technical repair to public health outcomes [11]. When developing nutritionally enhanced or novel protein foods, it is essential to address potential sensory defects through flavor science (e.g., off-flavor masking, flavor enhancement, texture modification) to ensure healthy foods are also a pleasurable sensory experience. Therefore, sensory design must proceed in parallel with product development.

6. Conclusion

Through a systematic literature review, this study constructs and argues for an integrated "Nutrition Chain Repair" framework targeting hidden hunger. The core argument is that hidden hunger is not merely a result of insufficient intake but the inevitable outcome of continuous, systemic breaks in the nutritional delivery function of the modern food system at three key nodes: the production source, processing and distribution, and assessment and cognition [1]. Therefore, fragmented improvements cannot cure the problem; cross-chain synergistic intervention is necessary to rebuild the integrity of the nutrition flow.

The first node of the framework focuses on repair at the production source. The study indicates that to address the nutrient "dilution effect" in crops caused by the "Green Revolution," active strategies to increase nutrient density are imperative [1]. Biofortification, by breeding micronutrients directly into the genome of staple crops, represents a paradigm shift from "external addition" to "internal enhancement," providing a sustainable solution for improving population nutrition at the source [3]. Concurrently, to break the resource boundaries of traditional agriculture, the framework emphasizes the importance of expanding the nutritional resource pool. This includes developing "future foods" like algal protein, with its dual advantages of high nutrient density and low environmental footprint [4], and the high-value utilization of seafood processing by-products, applying circular economy principles to transform waste into new nutritional inputs [5].

At the second node, repair in processing and delivery, the framework posits that technological innovation should transform this "risk point" for nutrient loss into a "value-added point." Process optimization is the fundamental defense; for example, precise control of freezing rates and frozen storage temperatures can minimize drip loss and protein denaturation in meat processing, thereby preserving its nutritional value [6]. Biotransformation, particularly traditional fermentation, utilizes microbial pre-digestion and synthesis to enhance the bioavailability and functionality of nutrients in food [8]. Advanced delivery systems, such as liposomal encapsulation, represent the cutting edge of proactive repair, providing a "nano-protective capsule" for sensitive nutrients, enabling their

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controlled and targeted delivery in vivo, and revolutionizing the precision and efficiency of nutritional interventions [7].

The third node focuses on repairing the assessment and cognition system, the cornerstone that ensures all interventions are correctly directed. At the data level, the current protein assessment method based on a generic conversion factor (N×6.25) is systematically flawed, urgently requiring a transition towards accurate assessment based on food-specific factors or amino acid analysis to solidify the metrological foundation of all nutritional research [2]. In the cognitive paradigm, it is essential to move beyond "nutritional reductionism," which simplifies food to a list of nutrients, and instead adopt a food-matrix systems view. This theory reveals that the physical structure of food governs the release and metabolic kinetics of nutrients, is key to understanding the health effects of whole foods, and provides the core principle for designing the next generation of healthy foods [9]. Furthermore, the integration of nondestructive testing technologies like magnetic resonance provides a "transparent view" for the real-time monitoring and quality assurance of the aforementioned repair processes [10].

Finally, this study clarifies that the public health value of all technical repairs ultimately depends on their long-term adoption by consumers. Therefore, flavor perception science is the critical bridge that consistently connects technology and the market [11]. Successful products must, through sensory design, address potential sensory deficiencies that may arise from nutritional enhancement or novel ingredients, ensuring healthy choices are also pleasant experiences.

The "Nutrition Chain Repair" framework stems from the theoretical synthesis and logical construction of cutting-edge evidence. Its core value lies in providing a systematic, actionable blueprint. However, it must be noted that the large-scale application of this framework still faces multiple validation challenges: First, effectiveness must be verified through well-designed randomized controlled trials and community intervention projects in real-world settings to confirm its efficacy in improving the nutritional status of specific populations. Second, economic feasibility needs assessment, particularly the cost-benefit ratio of some advanced technologies (e.g., liposomal encapsulation, large-scale MR monitoring) and their accessibility in resource-limited areas. Third, cultural adaptability cannot be ignored; the strategies within the framework (e.g., promoting fermented foods, and algal protein) need localized adjustments considering the dietary culture, consumption habits, and acceptance in different regions.

Based on this, future research should focus on three key directions to advance the framework from concept to practice: First, technological innovation and engineering. Focus on developing more cost-effective, scalable nutrient delivery carriers and food texture design technologies to lower the application threshold of advanced solutions. Second, evidence generation and mechanistic understanding. Vigorously conduct clinical nutrition and population studies based on the concepts of "whole food" and "food matrix," not only validating health benefits but also deeply elucidating the underlying mechanisms of digestion, absorption, metabolic regulation, and gut microbiota interaction, accumulating high-level scientific evidence. Third, system environment and policy innovation. Explore and pilot innovative policy and economic tools, such as incorporating nutrient density into agricultural procurement standards, implementing "true cost pricing" reflecting health and environmental externalities, and designing fiscal schemes to incentivize consumers to choose healthy foods. The ultimate goal is, through cross-sectoral, multi-level collaborative efforts, to systematically reshape the food environment, making the repair of the nutrition chain an endogenous driver, thereby fundamentally reversing the difficult situation of hidden hunger on a global scale.

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