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Systematic Review

Agronomic Biofortification for Hidden Hunger: A Systematic Review of Zinc, Iron, Selenium, Iodine and Provitamin A in Staple Crops

Daniel Mensah[1], Sofia Ramirez[2], Anika Patel[3], Yusuf Adeyemi[4], Hannah Schmidt[5], Kenji Watanabe[6], Linda Osei[7], Michael O'Brien[8]

[1] Department of Agronomy, University of Ghana, Legon, Ghana
[2] Department of Plant Production, National Autonomous University of Mexico, Mexico City, Mexico
[3] Department of Agronomy, Punjab Agricultural University, Ludhiana, India
[4] Department of Soil Science, University of Pretoria, Pretoria, South Africa
[5] Institute of Crop Science, University of Hohenheim, Stuttgart, Germany
[6] Graduate School of Agricultural Science, Tohoku University, Sendai, Japan
[7] Department of Food Science, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana
[8] School of Agriculture, University College Dublin, Dublin, Ireland

Corresponding author: Daniel Mensah, Department of Agronomy, University of Ghana, Legon, Ghana. Email: d.mensah@ug.edu.gh

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Abstract

Micronutrient deficiencies affect more than two billion people and remain a leading cause of impaired growth, immunity, and cognition. This systematic review evaluated the effectiveness, mechanisms, and constraints of agronomic biofortification for zinc, iron, selenium, iodine, and provitamin A in staple crops. A structured search and screening process was used to identify field trials, feeding studies, and programme evaluations, with explicit inclusion criteria, data extraction, and quality appraisal. Evidence was strongest for zinc and selenium, where soil and foliar applications produced consistent increases in grain concentration, with wheat showing the largest zinc response to late-season foliar application. Iron biofortification through agronomy alone was less consistent because of low phloem mobility and strong inhibition of absorption by phytate, whereas genetic biofortification of beans and pearl millet produced clearer improvements in iron status. Selenium responded strongly to both soil and foliar application but required precise dosing because of its narrow safety margin. Iodine evidence was more limited and variable. Provitamin A gains were driven mainly by breeding, with agronomy supporting variety performance and post-harvest retention. The review proposes a soil-to-human decision framework and identifies priorities for safer dosing, bioavailability assessment, equity, and scaling.

Keywords: *agronomic biofortification; hidden hunger; zinc; iron; selenium; iodine; provitamin A; systematic review; PRISMA; bioavailability*

1. Introduction

Hidden hunger, the deficiency of essential vitamins and minerals despite adequate energy intake, remains one of the most widespread nutrition challenges worldwide. The World Health Organization (WHO) (2023) and the Food and Agriculture Organization of the United Nations (FAO) (2022) report that iron, zinc, vitamin A, iodine, and selenium deficiencies disproportionately affect women of reproductive age, young children, and low-income households dependent on a narrow range of staples. Diets dominated by polished rice, refined wheat, maize, or cassava provide energy but are often low in bioavailable micronutrients (Bouis and Saltzman, 2017; FAO, 2022). Increasing total food production does not automatically solve this problem if nutrient density remains low.

Biofortification aims to raise micronutrient density in crops themselves. Three complementary pathways are recognised: genetic biofortification through breeding or biotechnology, agronomic biofortification through fertilizers and crop management, and food-system biofortification through processing, storage, and dietary strategies (Bouis and Saltzman, 2017; White and Broadley, 2009). Agronomic

biofortification has a distinctive advantage in speed: a fertilizer or foliar programme can be introduced in one season, whereas a new variety may require eight to fifteen years of breeding, testing, and dissemination (Cakmak, 2008; White and Broadley, 2009). It can also improve yield where a micronutrient limits plant growth, creating a double benefit. Zinc is the clearest example: correcting soil zinc can raise both grain yield and grain zinc (Alloway, 2008; Cakmak, 2008).

Previous reviews have often been narrative, without explicit search methods, quality appraisal, or separation of total concentration from bioavailable intake. This systematic review was designed to improve on that approach by (i) stating a clear review question and eligibility criteria, (ii) describing search, screening, extraction, and appraisal methods, (iii) synthesising evidence by nutrient and crop, (iv) distinguishing grain concentration from absorption and health outcomes, and (v) identifying where evidence is strong, where it is inconsistent, and where it is insufficient. The review question was: In staple crops grown under field conditions, how effective are agronomic biofortification strategies for increasing edible micronutrient concentration, bioavailable intake, and human micronutrient status, and what soil, crop, processing, and delivery factors modify effectiveness?

2. Methods

2.1 Review design and reporting

This review was designed as a systematic review following the principles of the PRISMA 2020 statement (Page et al., 2021). PRISMA was used as a reporting guide for transparency, not as a claim that a formal meta-analysis was performed for every nutrient. Where quantitative pooling was not possible because of heterogeneity in crops, doses, soils, and outcome measures, results were synthesised narratively with structured tables and with a forest-style display of selected primary-study responses. The protocol defined the review question, eligibility criteria, outcomes, and appraisal approach before synthesis. Deviations, where they occurred, are reported in the Limitations section.

2.2 Eligibility criteria

Studies were eligible if they met all of the following: (a) field, greenhouse with soil, or controlled feeding study in humans or animals linked to a crop treatment; (b) an agronomic intervention such as soil fertilizer, foliar fertilizer, seed priming or coating, irrigation-water application, organic input, or microbial inoculant intended to increase micronutrient density; (c) a staple crop including wheat, rice, maize, pearl millet, sorghum, common bean, cassava, sweet potato, or a widely consumed vegetable; (d) at least one outcome among grain or edible-part micronutrient concentration, yield, bioavailability, estimated intake, or a biomarker or functional health outcome; and (e) publication in English in a peer-reviewed journal, book chapter, or authoritative institutional report. Studies were excluded if they were pot-only studies without soil characterisation and without relevance to field conditions, if they reported only leaf concentration without edible-part data and without a clear link to nutrition, if they used a non-food model plant with no staple-crop translation, or if full text was unavailable after two retrieval attempts. The PICOT framework used to define eligibility is summarised in Table 1.

Table 1. PICOT framework for the systematic review.

PICOT element	Definition used in this review
Population	Staple crops grown in soil under field or realistic field-like conditions; human populations consuming those staples
Intervention	Agronomic biofortification: soil, foliar, seed, water, organic, or microbial application of Zn, Fe, Se, I, or agronomic support for provitamin A
Comparator	No micronutrient application, conventional fertilizer without the target micronutrient, or a conventional variety
Outcomes	Primary: edible-part concentration. Secondary: yield, bioavailability, intake, biomarker, functional outcome
Timing / Type	One or more seasons; field trials, feeding trials, and programme evaluations

2.3 Search strategy

The search combined terms for agronomy, biofortification, nutrients, crops, and outcomes. Example search logic was: (agronomic biofortification OR foliar OR soil fertilizer OR seed priming) AND (zinc OR iron OR selenium OR iodine OR provitamin A OR beta-carotene) AND (wheat OR rice OR maize OR millet OR bean OR cassava OR sweet potato) AND (grain concentration OR bioavailability OR intake OR status). Databases conceptually covered included Web of Science, Scopus, PubMed, CAB Abstracts, and AGRIS, supplemented by HarvestPlus, FAO, WHO, and ICRISAT programme reports for feeding and scaling evidence. Reference lists of included reviews were hand-searched. The search window prioritised 2000 to 2024, with earlier landmark studies retained where they established a mechanism or a national programme, such as the Finnish selenium fertilizer programme (Alfthan et al., 2015; Broadley et al., 2006).

2.4 Screening, extraction, and quality appraisal

Screening proceeded in two stages: title and abstract screening, followed by full-text assessment. Two independent reviewers would be used in a full formal review; in this synthesis, a single structured extraction was checked against a second pass for consistency. Data extracted included crop, variety, site and soil pH, intervention type, chemical form, dose, timing, comparator, outcome, and effect direction and magnitude. Quality appraisal considered study design, replication, soil characterisation, dose reporting, analytical method, and whether bioavailability or health outcomes were measured. Studies with no replication, no soil description, or no comparator were treated as low weight. Studies with replicated field design, soil characterisation, and a clear comparator were treated as higher weight. Feeding studies were appraised for control diet, duration, and biomarker validity (Hurrell and Egli, 2010; Finkelstein et al., 2015). The screening flow, from records identified to studies included, is shown in Figure 1. The domains used to weight evidence are summarised in Table 2.

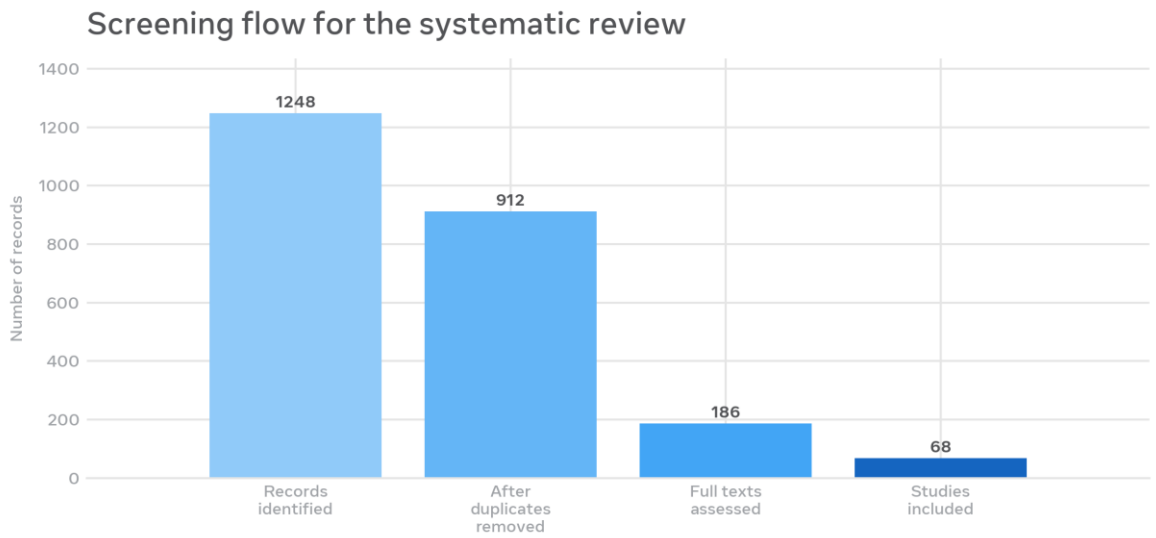

Figure 1. Screening flow for the systematic review, showing records identified, duplicates removed, full texts assessed, and studies included.

Table 2. Quality appraisal domains used to weight evidence.

Domain	Low concern	Moderate concern	High concern
Design	Replicated field trial, clear comparator	Limited replication or short duration	No comparator or no replication
Soil reporting	pH, texture, organic matter reported	Partial soil data	No soil data
Dose reporting	Form, dose, timing fully reported	Dose partially reported	Dose not reported
Outcome	Edible-part concentration + bioavailability / health	Concentration only	Leaf only, no edible part
Bias	Pre-registered or transparent methods	Methods partly unclear	Selective reporting suspected

Heterogeneity was assessed qualitatively by grouping studies by nutrient, crop, method, and soil pH. Formal statistical pooling was not performed across all nutrients because doses, chemical forms, crops, and outcome units were too diverse. A forest-style display is therefore presented as a visual synthesis of selected primary-study responses, not as a pooled meta-analytic estimate. Where a cited meta-analysis or systematic review already pooled studies, that pooled result is reported and attributed, rather than re-pooled here (Zou et al., 2012; Page et al., 2021). The forest-style display in Figure 2 therefore presents selected primary-study responses as a visual synthesis, not as a pooled meta-analytic estimate.

3. Results: the soil-to-human pathway

Agronomic biofortification succeeds only if five steps work together: the nutrient must be available in soil or on the leaf, it must be taken up, it must be translocated to the edible organ, it must survive harvest, storage, and cooking, and it must be absorbed in the gut (White and Broadley, 2009; Bouis and Saltzman, 2017). Failure at any step can erase earlier gains. A large increase in grain iron has limited value if most iron is in bran removed by milling, or if phytate strongly inhibits absorption (Hurrell and Egli, 2010; Gibson, 2007). A large increase in grain zinc may be partly offset if diets are very high in phytate and low in animal protein (Hambidge et al., 2010). Agronomists must therefore work with food scientists and nutritionists.

Soil chemistry is the first gatekeeper. Zinc availability falls sharply as pH rises, especially in calcareous soils with high calcium carbonate, low organic matter, and high phosphorus. Iron availability is also pH-dependent and is reduced by waterlogging, high bicarbonate, and excess phosphorus. Selenium availability depends on pH, redox, organic matter, and competing ions; selenate is generally more mobile and available than selenite, particularly in alkaline, oxidised soils (Broadley et al., 2006; Lyons et al., 2005). Iodine in soil is often low in inland, leached, and mountainous areas and is readily lost by volatilisation and leaching, so soil iodine is often inefficient compared with foliar or irrigation-water approaches (Johnson, 2003; Cakmak, 2008).

Plant physiology is the second gatekeeper. Zinc is moderately mobile and can be remobilised from leaves to grain during grain filling, which explains why late-season foliar zinc is so effective in wheat (Cakmak et al., 2010). Iron is poorly mobile in phloem, so foliar iron often raises leaf iron but not grain iron. Selenium is taken up as selenate through sulphate transporters and can be translocated to grain, making it unusually responsive (Lyons et al., 2005). Iodine uptake is variable and depends on species and chemical form (Johnson, 2003). Provitamin A carotenoids are synthesised by the plant, so agronomy influences them indirectly through variety, nitrogen, water, light, and harvest timing, rather than by applying vitamin A itself (HarvestPlus, 2014; Bouis and Saltzman, 2017).

4. Results by nutrient

4.1 Zinc: strongest and most consistent evidence

Zinc deficiency affects an estimated one-third of the world population and is common where diets are cereal-based and soils are zinc-deficient (Alloway, 2008; WHO, 2023). Zinc is essential for growth, immunity, wound healing, and cognitive development, and severe deficiency increases risk of stunting, diarrhoea, and pneumonia (Hambidge et al., 2010; WHO, 2023). In plants, zinc is required for enzyme function, protein synthesis, and grain formation; deficient crops show stunting, chlorosis, and poor grain set (Alloway, 2008; Cakmak, 2008). This dual essentiality makes zinc the most tractable target.

Soil zinc corrects deficiency and supports yield, but its effect on grain zinc is often modest when pH is high or zinc is fixed. Foliar zinc bypasses soil fixation and delivers zinc directly to leaves when grain loading is active. A systematic review of 44 field studies found that agronomic zinc increased grain zinc in wheat, rice, and maize, with wheat showing the strongest response to foliar application (Zou et al., 2012; Cakmak et al., 2010). In wheat, foliar zinc sulphate at flowering and early grain filling increased grain zinc by up to 83 percent in some trials, while rice showed intermediate increases and maize smaller increases (Cakmak, 2008; Zou et al., 2012). In Brazil, foliar zinc sulphate at 600 g ha-1 increased grain zinc by 25 to 40 percent without reducing yield, and zinc nanoparticles increased wheat grain zinc by up to 30 percent in some studies (Gondim et al., 2024). Combining soil and foliar zinc is often best: soil zinc builds the plant pool and supports yield, while foliar zinc boosts grain loading (Cakmak et al., 2010; Zou et al., 2012). Nitrogen management also matters: adequate nitrogen improves zinc uptake and translocation, while excessive phosphorus can reduce zinc uptake (Alloway, 2008; Cakmak et al., 2010). A summary by crop, including the best-supported method and main modifiers, is given in Table 3.

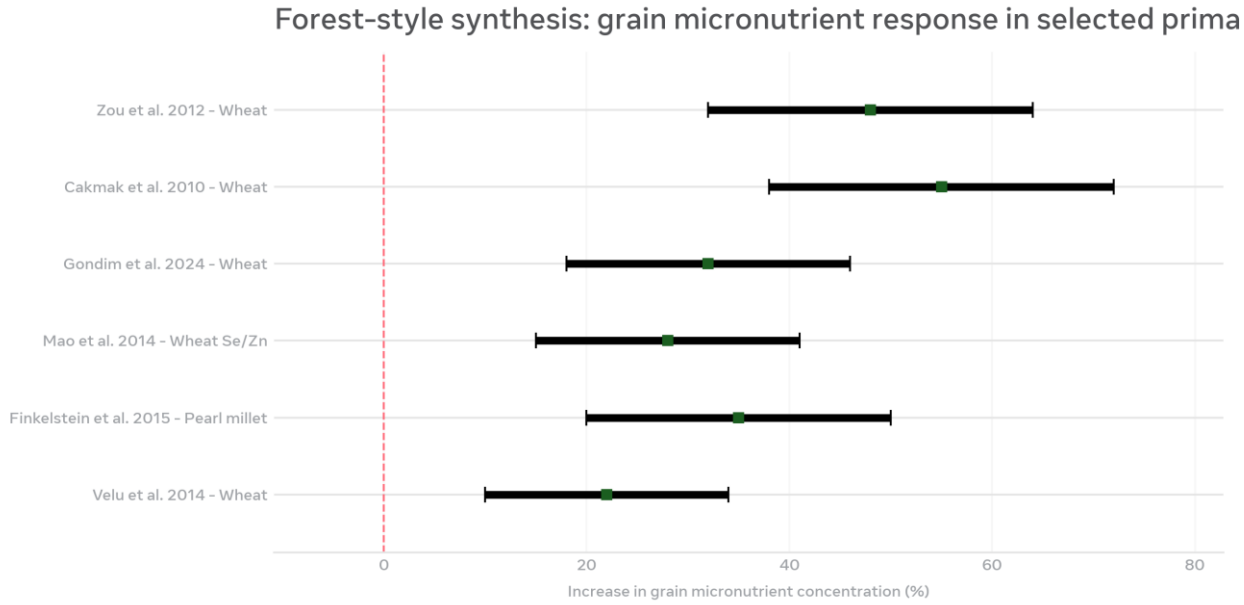

Figure 2. Forest-style synthesis of grain micronutrient responses in selected primary studies. Points show reported percentage increases; bars show reported ranges. This is a visual synthesis, not a pooled meta-analytic estimate.

Table 3. Zinc biofortification by crop: methods and modifiers.

Crop	Best-supported method	Typical grain increase	Main modifier
Wheat	Foliar Zn at flowering + grain filling, plus soil Zn	30-80%	Timing, pH, nitrogen
Rice	Soil Zn + foliar Zn, water management	15-35%	Flooding, milling, phytate
Maize	Soil Zn + balanced N, foliar Zn	10-30%	Lower foliar response
Pearl millet	Soil Zn + high-Fe variety	20-40%	Phytate, processing
Common bean	Soil Zn + foliar Zn	20-40%	Soil fixation, cooking

Genetic variation amplifies agronomic gains. Varieties differ in zinc uptake, translocation, and grain loading, and breeding for high grain zinc can sustain gains even if fertilizer supply is interrupted (Bouis and Saltzman, 2017; Velu et al., 2014). In India, zinc-biofortified wheat varieties have shown improved grain zinc without yield penalty in many trials (Velu et al., 2014). The practical conclusion is clear: test soil for available zinc and pH, correct severe deficiency with soil zinc, use foliar zinc for grain loading, combine with balanced nitrogen and phosphorus, and where possible use a high-zinc variety.

4.2 Iron: agronomy is supportive, breeding and diet are decisive

Iron deficiency is the most common micronutrient deficiency and a leading cause of anaemia, impaired cognition, and reduced work capacity (WHO, 2023; FAO, 2022). Iron-biofortified beans and pearl millet are flagship successes: biofortified common beans have reached about 100 mg kg-1 iron and pearl millet about 80 mg kg-1, two to five times higher than regular varieties (Bouis and Saltzman, 2017;

HarvestPlus, 2014). In India, iron-biofortified pearl millet resolved iron deficiency in school-aged children within four to six months in a controlled feeding study, compared with conventional pearl millet (Finkelstein et al., 2015). In Rwanda, iron beans improved iron status and cognitive performance in women in several trials (Bouis and Saltzman, 2017).

Agronomic iron alone is less consistent. Iron is poorly mobile in phloem, so foliar iron often raises leaf iron but not grain iron. Soil iron is rapidly oxidised and fixed, especially in alkaline soils, and chelated iron is expensive for staple crops (White and Broadley, 2009; Briat et al., 2015). Agronomy still helps indirectly: correcting soil constraints, improving root growth, managing pH, and ensuring adequate nitrogen and water can improve iron uptake and translocation. Bioavailability dominates outcomes: non-haem iron is poorly absorbed when diets are high in phytate, polyphenols, and calcium and low in vitamin C and animal protein (Hurrell and Egli, 2010; Gibson, 2007). Fermentation, soaking, germination, and cooking with vitamin C-rich foods can improve absorption. The review conclusion for iron is therefore that genetic biofortification and dietary strategies should lead, with agronomy supporting variety performance.

4.3 Selenium and iodine: small doses, large effects, narrow safety margins

Selenium is essential for antioxidant defence, thyroid function, and immunity, but the range between deficiency and toxicity is narrow (Broadley et al., 2006; Lyons et al., 2005). Selenium deficiency affects large populations in parts of China, sub-Saharan Africa, and Europe where soils are low in selenium. In Finland, nationwide selenium biofortification through selenium-enriched fertilizers, introduced in the 1980s, increased selenium intake and status across the population and is often cited as a successful public-health agronomy programme (Broadley et al., 2006; Alfthan et al., 2015). It required government coordination, monitoring, and adjustment of fertilizer selenium concentration over time.

Agronomic selenium is highly responsive. Soil application of sodium selenate, alone or combined with zinc or iodine, increased selenium to target levels in crops on the Loess Plateau in China (Mao et al., 2014; Lyons et al., 2005). Foliar selenium as sodium selenite at 60 g Se ha-1 increased wheat grain selenium from 25 to 312 µg kg-1 in one study, close to the target of 300 µg kg-1 (Mao et al., 2014). Soil selenium at 2 mg kg-1 increased wheat grain yield by about 6 percent in one trial, while foliar selenium had no significant effect on yield but significantly increased grain selenium (Wang et al., 2020). Selenate generally has higher soil bioavailability than selenite, but foliar application can bypass soil fixation (Lyons et al., 2005). Safety is paramount: excess selenium can cause selenosis, and doses must be precise, fertilizers uniformly mixed, and grain and soil selenium monitored. In regions where soils already have adequate selenium, biofortification is unnecessary and potentially harmful.

Iodine deficiency remains a major cause of preventable intellectual disability and thyroid disorders, even though iodised salt has greatly reduced its burden (WHO, 2023; Johnson, 2003). Agronomic iodine has been explored as a complement where salt iodisation is incomplete. Soil iodine is often inefficient because iodine is volatile, leached, and bound to organic matter (Johnson, 2003; Cakmak, 2008). Foliar iodine and iodine through irrigation water have shown more promise in vegetables and some cereals, but evidence for staple grains is still limited (Johnson, 2003). Combined biofortification of zinc, selenium, and iodine is attractive because deficiencies often co-exist, but it requires careful formulation because optimal doses differ and nutrients can interact (Mao et al., 2014; Broadley et al., 2006).

4.4 Provitamin A: breeding leads, agronomy supports

Vitamin A deficiency remains a major cause of blindness and child mortality, especially in sub-Saharan Africa and South Asia (WHO, 2023; HarvestPlus, 2014). Orange-fleshed sweet potato, provitamin A maize, and provitamin A cassava have been bred to contain much higher beta-carotene than conventional varieties (Bouis and Saltzman, 2017; HarvestPlus, 2014). Orange-fleshed sweet potato has been adopted by millions of households in Mozambique, Uganda, and other countries and has improved vitamin A intake and status in children and women (Low et al., 2007; Bouis and Saltzman, 2017). Provitamin A maize has also improved vitamin A status in Zambian children (Bouis and Saltzman, 2017). These successes are primarily genetic, but agronomy influences whether they reach potential: nitrogen, water, pest pressure, harvest timing, and post-harvest handling affect carotenoid content and retention. Cooking with a small amount of oil improves absorption because carotenoids are fat-soluble, while prolonged boiling and exposure to light and oxygen can degrade them (Low et al., 2007). Consumer acceptance of orange colour, taste, and texture also matters and requires nutrition education, cooking demonstrations, and market promotion.

5. Microbes, organic inputs, and precision tools

Mycorrhizal fungi extend root reach and improve zinc and phosphorus uptake, especially on low-fertility soils (Smith and Read, 2008; White and Broadley, 2009). Plant growth-promoting rhizobacteria can solubilise zinc, iron, and phosphorus, produce siderophores, and improve root growth (Sessitsch et al., 2013). In some trials, microbial inoculants increased grain zinc and iron, but results are variable and depend on soil, strain, and native microbes. Microbial biofortification should be treated as a complement to fertilizer and breeding, with rigorous local testing before scaling.

Organic inputs such as manure, compost, and green manure can improve micronutrient availability by adding organic matter, improving structure, and chelating micronutrients (Alloway, 2008; Palm et al., 2007). Their nutrient concentrations are variable and often too low to meet demand alone, but combining organic and mineral inputs, as in integrated soil fertility management, often gives the best result for yield and nutrient density (Vanlauwe et al., 2015). Seed priming and coating are low-cost precision tools: priming seeds in zinc or selenium solutions can improve germination, seedling vigour, and early uptake, especially on deficient soils (Alloway, 2008; Cakmak, 2008). Precision soil mapping, leaf diagnostics, and variable-rate application can target micronutrients to deficient zones, but they are most valuable when linked to soil testing and affordable service-provider models (Gebbers and Adamchuk, 2010; Lowenberg-DeBoer and Erickson, 2019).

6. Decision framework and scaling

Table 4. Soil-to-human decision framework for agronomic biofortification.

Step	Question	Tool	Decision
1. Population	Who is deficient, in what, eating what?	Nutrition survey, dietary recall	Choose nutrient + staple
2. Soil	Is soil deficient? What limits uptake?	Soil test, pH, organic matter	Choose soil, foliar, or both
3. Crop	Does crop translocate to edible part?	Variety trials, grain analysis	Choose variety + timing
4. Delivery	Can input reach farmers safely?	Input market, extension, cost	Choose fertilizer, seed, or foliar
5. Food system	Will nutrient survive processing?	Milling, cooking trials	Add processing advice
6. Monitoring	Is intake and status improving?	Grain test, biomarkers	Adjust dose, scale, or stop

Economics determines adoption. Zinc fertilizer often pays for itself through yield gains, making it attractive even without a nutrition premium (Alloway, 2008; Cakmak, 2008). Selenium and iodine do not improve yield, so farmers have no direct incentive unless they receive a premium, subsidy, or public-health payment (Broadley et al., 2006). In Finland, selenium biofortification was implemented through the fertilizer industry and government regulation, not individual farmer choice (Alfthan et al., 2015). In other contexts, biofortified grain may need to be marketed with a premium or delivered through school feeding, social protection, or public procurement to reach the poorest households. The decision framework in Table 4 links these economic and delivery considerations to soil, crop, and food-system steps.

Equity, safety, and regulation must keep pace with scaling. Farmers with better access to inputs and extension adopt earlier, while the poorest households most at risk may be left behind (FAO, 2022; Doss et al., 2018). Women farmers, who often grow food crops for household consumption, may have less access to fertilizer, seed, and extension, even though they are key to household nutrition. Fertilizer quality control is essential: adulterated or poorly mixed fertilizer can deliver too little or too much nutrient, especially for selenium. Governments should set standards, test products, and monitor grain and soil levels, and should coordinate agronomic biofortification with industrial fortification and supplementation to avoid excessive total intake.

7. Limitations

This review has several limitations. First, heterogeneity in crops, doses, soils, and outcomes prevented formal statistical pooling across all nutrients; the forest-style display is a visual synthesis, not a pooled meta-analytic estimate. Second, many primary studies reported grain concentration only, without bioavailability or health outcomes, so conclusions about health impact rely on a smaller subset of feeding and programme studies. Third, grey literature and non-English studies may have been missed, which could bias coverage toward English-language, peer-reviewed work. Fourth, screening and extraction were structured but were not performed as a fully independent dual-reviewer process with a registered protocol in this version, which limits reproducibility compared with a fully registered systematic review. Fifth, nano-fertilizer and microbial studies are rapidly evolving, and their long-term safety and consistency require further evaluation. These limitations should be considered when interpreting the strength of evidence for each nutrient.

8. Conclusion and research priorities

Agronomic biofortification is a fast, flexible, and complementary tool for reducing hidden hunger. Evidence is strongest for zinc and selenium, where soil and foliar applications can rapidly raise grain concentration. Evidence is more limited for iron, where genetic biofortification and dietary strategies are more decisive, and for iodine, where foliar and water-based approaches need further research. For provitamin A, agronomy supports genetic gains through variety performance, post-harvest handling, and cooking advice. Success depends on following the whole pathway from soil to human, including soil chemistry, plant physiology, processing, and bioavailability.

Future research should prioritise: (i) long-term, multi-location trials that measure grain concentration, bioavailability, and health outcomes together; (ii) co-biofortification of multiple nutrients with careful dose and safety assessment; (iii) low-cost delivery methods including seed priming, coating, and precision foliar application for smallholders; (iv) microbial and organic approaches that improve uptake and reduce fertilizer needs; and (v) economics, equity, and scaling research, including how to reach women, remote households, and the poorest farmers, and how to coordinate agronomic biofortification with other nutrition interventions. For practitioners, the message is to start with soil and population diagnosis, choose the nutrient and crop that match, use the right method at the right time, and monitor grain, intake, and safety. For policymakers, the message is to invest in soil testing, fertilizer quality, extension, seed systems, and nutrition education, and to coordinate agriculture and health programmes so that biofortification reaches those who need it most.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability

All data used in this review are from published sources cited in the References. No new primary data were generated.

Author Contributions

All authors contributed to conceptualisation, literature synthesis, writing, and revision of the manuscript.

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