

Review

Biofortification of Common Bean: Critical Analysis of Genetic and Agronomic Strategies as Viable Alternatives to Tackling Zinc Deficiency in Developing Countries

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Abstract

Zinc (Zn) deficiency affects over 30% of the global population, with the highest burdens in developing countries reliant on cereal-based diets. As a major dietary staple in regions such as Sub-Saharan Africa and Latin America, common bean (*Phaseolus vulgaris* L.) represents a promising vehicle for addressing hidden hunger. This review critically evaluates the efficacy of various strategies to enhance Zn concentration in common bean, ranging from agronomic to genetic manipulation, and proposes promising strategies for biofortifying common bean in developing countries that are resource- and technology-limited. Biofortification strategies include agronomic practices, conventional breeding, and genetic engineering, each with distinct strengths and limitations. Agronomic methods such as soil and foliar fertilization can rapidly increase micronutrient content, but they require recurrent costs and may not be sustainable for smallholders without subsidies. Genetic engineering, particularly transgenic approaches, can significantly boost Zn levels; however, regulatory hurdles, cost of production, and public acceptance remain significant obstacles to widespread adoption. Conventional breeding is secure and widely adopted, but is time-consuming and limited by genetic diversity, making it less precise and slower than genetic engineering. We argue for a context-specific and integrated biofortification framework that prioritizes agronomic interventions such as biofertilizer, seed priming, soil Zn application, and foliar Zn application as approaches for quick results. Moderate- to long-term progress towards a biofortified common bean can be achieved using conventional breeding methods by selecting for local germplasm that accumulates higher Zn amounts in grain. On the other hand, genetic engineering is best for rapid, targeted nutrient enhancement where genetic diversity is lacking, but faces regulatory and acceptance challenges. We recommend that policymakers prioritize frameworks that harmonize these approaches, improve communication and education regarding the benefits of biofortified crop produce, subsidize and strengthen biofortified seed systems, and promote soil health initiatives.

Keywords: hidden hunger; agronomic biofortification; genetic biofortification; human health



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1. Introduction

Common bean (*Phaseolus vulgaris* L.) is a key agronomic crop cultivated globally and plays a critical role in ensuring food security, improving nutrition, and reducing poverty [1]. This is particularly true in developing countries like Malawi, where beans are a staple food, with daily consumption reaching up to 107 g [2–4]. Therefore, the composition and nutritional concentrations of common bean have a substantial impact on human health [5,6]. Zinc content in the edible parts of the crop mainly depends on plant acquisition efficiency, Zn availability in the soil, and internal remobilization [7–9]. Zinc deficiency in agricultural soils is considered to be the most geographically widespread micronutrient deficiency. Consequently, low Zn in edible parts in extreme cases leads to manifestations of hidden hunger [10,11]. As the population of developing countries is increasing alarmingly, the condition will be even more serious than expected in the near future if no urgent remedial options are deployed to address hidden hunger. Some of the effective options to solve the current predicament are supplementation, dietary diversification, fortification, and biofortification [12]. We also acknowledge that a problem so widespread needs more than just one set of solutions or interventions to have an appreciable impact. Figure 1 summarizes the need for biofortification as a viable alternative to tackling Zn deficiency in developing countries.

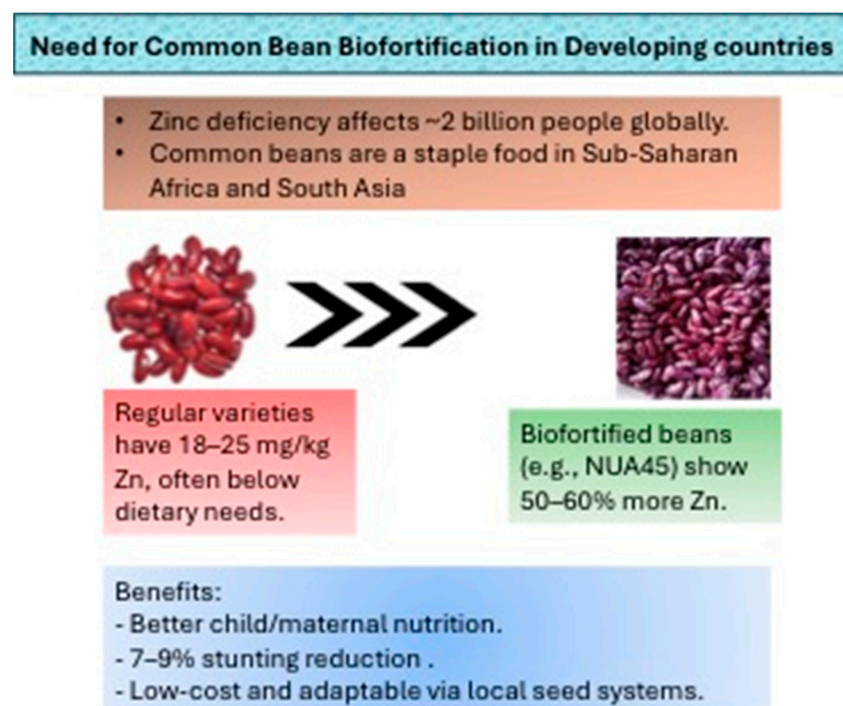


Figure 1. The need for common bean biofortification in developing countries.

Copenhagen Consensus in 2008 ranked biofortification among the top five most cost-effective interventions to combat hidden hunger [13]. The underlying rationale is that millions of people in resource-poor settings cannot afford a varied diet rich in micronutrients. Biofortification involves enhancing the nutritional quality of food crops through biological means in a cost-effective and sustainable manner [14,15]. This can be achieved through either genetic (conventional plant breeding, genetic modification, and omics-driven) or agronomic approaches, which involve the use of micronutrient fertilizers and nutrient priming.

Zinc plays crucial biological roles, functioning as a catalyst, a structural component, and a regulatory ion [16]. The recommended daily intake of Zn ranges from 8 to 11 mg/day

for adults and 5 mg/day to 8 mg/day for children, depending on age and gender [17]. However, in many developing countries, this recommendation is often unmet due to diets that contain lower Zn content [18]. This has led to acute Zn deficiency in many populations. For instance, while the global Zn deficiency rate is 33%, the prevalence in developing countries like Malawi and Ethiopia is as high as 62% and 81%, respectively [19,20]. Inadequate Zn intake results in physiological disorders impacting the immune, gastrointestinal, epidermal, central nervous, skeletal, and reproductive systems [21,22]. It is, therefore, vital that Zn levels in foods are increased to improve human and animal health. Some studies indicate that Zn enrichment is possible through Zn fertilization, and the magnitude of this boost depends on the time of application, crop, and the cultivar grown [23,24]. Researchers around the world have already shown that vitamin A, Fe, and Zn deficiencies may be overcome through biofortification of staple food crops [15,18,25–31].

Despite the growing literature on Zn biofortification, most reviews treat agronomic and genetic approaches as distinct or competing strategies. This review addresses a critical and under-explored gap by presenting a novel, integrative analysis of Zn biofortification strategies in common beans, evaluating both agronomic and genetic methods within a unified comparative framework. It assesses their relative effectiveness, scalability, and alignment with sustainability pillars such as equity, environmental impact, and long-term nutritional outcomes, particularly in resource-constrained settings where soil and dietary Zn deficiencies intersect. Specifically, it addresses the following research questions: (i) Which biofortification approaches are most effective for increasing Zn content in common beans? and (ii) How do these approaches compare in terms of feasibility in developing countries? By filling this critical gap, the review offers practical insights for breeding programs, policy development, and research targeting micronutrient malnutrition in vulnerable populations.

The remainder of this review is structured as follows: Section 2 details the biofortification methods; Section 3 presents a comparative evaluation of biofortification approaches; Section 4 discusses the status of biofortification in developing countries; Section 5 proposes promising implementation strategies to enhance biofortification of common bean in developing countries; and Section 6 concludes with research gaps and policy implications.

2. Biofortification Methods

Biofortification, which is the process of enhancing micronutrient content and availability in edible parts of crops during crop cultivation, is a more sustainable approach that is producing promising results when used alongside nutrition programs [15]. Biofortification strategies include agronomic practices, conventional breeding, genetic engineering, and Omics-driven approaches. While biofortification and other approaches are valuable tools in addressing hidden hunger, no single solution can fully resolve the issue on its own.

2.1. Agronomic Biofortification

Agronomic biofortification utilizes farming practices that increase Zn bioavailability and uptake in plants and specifically in edible parts of food crops [29,32]. This method is particularly important in regions where soil conditions, either chemical or physical, do not restrict Zn availability to plants [14]. The loading to the edible parts takes place either by direct uptake from the soil or by remobilization within the plant. Various agronomic biofortification techniques have been extensively tested for their effectiveness on common bean across different regions worldwide [14,18,29,31,33–35]. Among these, the most prominent methods include soil application, foliar application, and seed priming (Table 1).

Table 1. Effect of agronomic biofortification methods on Zn concentration (%) in common beans across countries.

Zinc Application Method	Application Rate	Fertilizer Used	Baseline (mg kg ⁻¹)	Final (mg kg ⁻¹)	% Increase	Country	Reference
Soil application	8 kg/ha	Zinc sulphate	42.7	46.4	8.7	Brazil	[36]
Soil application	15 kg/ha	Zinc sulphate	36.6	58.2	59.0	Tanzania	[37]
Soil application	20 kg/ha	Zinc sulphate	23.0	28.7	24.8	Kenya	[38]
Soil application	7.5 kg/ha	Zinc sulphate	27.0	43.0	59.3	Kenya	[27]
Foliar application	1.2 kg/ha	Zinc sulphate	15.3	20.7	35.3	Brazil	[34]
Foliar application	4 kg/ha	Zinc sulphate	68	78	15	China, India, and Zambia	[39]
Foliar application	0.6 kg/ha	Zinc sulphate	11.6	29.0	150	Brazil	[40]
Seed priming	0.7 mg/mL	Zn chelated by histidine	16.4	45.1	175	Iran	[41]

Soil application of micronutrients, considered one of the simplest biofortification techniques, is more common in cereal crops than in pulses [42]. Zn soil application is one of the viable alternatives that can be deployed to boost Zn assimilation in plant tissues and grains, especially in Zn-deficient soils. In addition, soil Zn application improves different physiological functions and results in better growth and high productivity [43]. The practice of adding fertilizers directly to the soil is both one of the oldest and the most common methods of enriching soils with essential nutrients. Today, it remains the most widely adopted approach for enriching crops, with an estimated 30–40% of farmers globally employing some form of soil enrichment, such as micronutrient fertilization with Zn and Fe, though adoption rates vary by region [44]. The popularity of soil application is due to its simplicity, cost-effectiveness, and scalability, making it the go-to solution for addressing nutrient deficiencies in crops [45]. We are cognizant that there are still some gaps in the efficacy of this approach in different conditions, such as the contribution of soil properties, root system architecture, method and rate of application, and time of application to the response of crops, especially Zn accumulation in edible parts. There is a need to address these gaps, and we anticipate that if these gaps can be addressed, it will provide guidance for enriching common bean grain Zn and optimizing Zn fertilization practices in common bean production, thereby addressing Zn hidden hunger in populations relying on common bean-based diets.

Foliar application of micronutrients involves directly applying nutrient solutions to the leaves, where they are absorbed and translocated to edible parts such as grains, fruits, and leaves [46]. This method is particularly effective for delivering micronutrients like Zn by bypassing soil-related limitations such as poor nutrient availability or adverse pH conditions [35]. Applications are typically carried out using techniques such as spray booms, mist sprayers, or aerial spraying. The success of foliar application, however, depends on factors including plant age, timing of application, weather conditions, and the crop's absorption efficiency [47]. In wheat, for instance, applying Zn later than the early milking stage reduced maximum grain Zn concentrations by 45% [48]. Although foliar application can rapidly correct nutrient deficiencies, it also presents challenges such as the need for multiple applications during the growing season and the risk of leaf burn if improperly applied [49,50].

Zinc seed priming, which involves soaking seeds in Zn-containing solutions like zinc sulfate (ZnSO_4) before planting, is an effective technique for improving seed germination, seedling vigor, root development, and crop Zn content [51,52]. It offers a cost-effective and easily adoptable option for smallholder farmers, requiring fewer inputs than foliar or soil fertilization [53]. The effectiveness of seed priming, however, depends on optimizing factors such as Zn concentration and soaking duration, as improper application can damage seeds or reduce nutrient uptake [54]. When properly managed, Zn seed priming provides a scalable solution for enhancing both crop productivity and nutritional quality, particularly in Zn-deficient regions. Recent advances indicate that seed priming with Zn oxide nanoparticles (ZnO NPs) offers superior biofortification benefits due to their enhanced solubility and bioavailability compared to conventional Zn sources. This approach has demonstrated notable potential in improving Zn uptake and overall plant performance. Functionalized ZnO NPs significantly increased Zn accumulation and biomass in wheat seedlings without compromising germination [55]. In rice, ZnO NPs enhanced Zn translocation, yield, and tolerance to moisture stress [56]. Similarly, ZnO NPs applied as nano-fertilizers elevated grain Zn concentrations, highlighting their value in micronutrient enrichment strategies [57]. Seed priming, when properly implemented, could be a scalable and low-cost agronomic biofortification strategy, particularly effective for smallholder farming systems in low-resource contexts.

The discovery of nanotechnology brings new prospects to increase food quality and safety through nano-enabled delivery systems. The utilization of nano-based fertilizers to improve biofortification has gained much attention in the last five years, offering a hopeful and optimistic outlook. Using nano-fertilizers for the biofortification of crops can be considered a promising method to deliver micronutrients for plants, surpassing the constraints of classic breeding. However, we are proposing comprehensive research on the use of nano-fertilizers in the agronomic biofortification of common bean and analyzing the beneficial impact of the use of nano-fertilizers in developing countries where this technology is currently nonexistent.

2.2. Genetic Biofortification

The genetic biofortification directly involves improving the genetic makeup of crops to produce desired nutritional profiles [58]. The principle behind genetic biofortification lies in modifying or selecting plant varieties that possess a natural or enhanced ability to take up, translocate, and store nutrients [29,56]. This is achieved through conventional breeding and various genetic engineering tools, such as transgenic crops or gene editing.

Conventional breeding focuses on combining desirable traits from different plants within the same or related species to create new cultivars with improved characteristics. This method primarily harnesses naturally occurring genetic variation to increase Zn content in crops by crossbreeding or selecting bean varieties that naturally accumulate higher levels of Zn [14]. This approach has been widely used to develop high-Zn common bean varieties taking advantage of the natural Zn variation within the genus, which ranges from 25 to 60 mg kg⁻¹ [59]. Researchers have successfully bred Zn-biofortified beans that can provide up to 70% of the recommended daily allowance (RDA) for Zn when consumed regularly [60]. These biofortified beans have been released in countries including Rwanda, Malawi, and the Democratic Republic of Congo, where beans are a staple food and Zn deficiency is a significant public health issue (Table 2).

Table 2. Zinc-biofortified common bean varieties and their countries of release.

Variety	Countries of Release	Zn Content (mg kg ^{−1})	References
NUA35	Rwanda, Colombia, Democratic Republic of Congo, Malawi	31–41	[61]
NUA45	Rwanda, Democratic Republic of Congo, Kenya, Malawi, Zambia, Eswatini, Mauritius, Mozambique, and Zimbabwe	10–40	[62]
RWR 2245	Rwanda, Democratic Republic of Congo, Uganda	34	[63]
CODMLB 001	Democratic Republic of Congo	*	[64]
MAC 44	Burundi	32	[65]
RWR 1129	Burundi	*	[65]

* Data not available.

Marker-assisted selection (MAS) improves the efficiency and precision of conventional breeding by allowing breeders to identify and select plants that carry genes associated with higher Zn accumulation, significantly accelerating the breeding process [66]. For Zn biofortification in common beans, several key genes involved in Zn uptake, transport, and accumulation have been identified and are now being utilized in marker-assisted selection (MAS) to accelerate the development of high-Zn genotypes. By leveraging genetic insights through marker-assisted selection (MAS), breeders have significantly shortened the time required to develop Zn-biofortified bean varieties from 8 to 10 years in conventional breeding programs to approximately 4–5 years while achieving substantially higher grain Zn concentrations [67]. However, MAS requires significant investment in molecular research and identifying quantitative trait loci (QTLs), which can be a challenge in resource-poor regions [68].

Genetic engineering focuses on introducing or modifying specific genes in a plant's genome to enhance Zn absorption from the soil, its transport within the plant, and accumulation in edible parts such as seeds [69]. Unlike conventional breeding and marker-assisted selection, which rely on natural genetic variability, genetic engineering enables the introduction of novel traits from other organisms, including bacteria and plants [70]. It often targets genes from the Zn/Fe-regulated transporter-like Protein (ZIP) family to improve Zn uptake and transport [69]. Overexpressing these transporters aims to increase Zn movement into seeds. Although genetic engineering offers considerable potential for micronutrient enhancement, there are currently no commercially released Zn-biofortified common bean varieties developed through genetic engineering. This is primarily due to challenges associated with reproducibility and limited success in achieving efficient *in vitro* regeneration. However, key genes regulating Zn uptake and transport, such as Phvul.011G035700 (bZIP23-like) and Phvul.003G086500 (OPT3-like), have been identified [71]. While the approach requires substantial investment, it offers a faster route to developing high-Zn bean varieties compared to traditional methods [72].

Omics-driven biofortification has emerged as a powerful approach to enhance the micronutrient density of common bean, a key dietary source of protein and minerals in many developing countries. Advances in genomics have enabled the identification of quantitative trait loci (QTLs) and candidate genes, such as members of the *PvZIP* transporter family, that regulate Zn and Fe accumulation in seeds [73]. Transcriptomic studies, using RNA sequencing, have revealed differential expression patterns of genes involved in metal transport and chelation [74] while proteomic analyses have identified metal-binding proteins and transporters that influence nutrient mobilization during seed development [75]. Metabolomics has provided insights into the composition of organic acids, phenolics, and antinutrients such as phytates, informing strategies to improve mineral bioavailability. Complementary

ionomic profiling enables simultaneous quantification of multiple elements, facilitating multi-nutrient breeding without compromising yield. Integrating these omics platforms allows for precise, data-driven selection of nutrient-dense genotypes and accelerates breeding cycles, offering a sustainable pathway to combat micronutrient deficiencies through biofortified common bean varieties.

3. Comparative Evaluation of Biofortification Approaches

Biofortification approaches to enhance crop nutrition include agronomic practices, conventional breeding, and genetic engineering, each with distinct strengths and limitations. Each approach has its merits and can be applied based on the nutrient target and local context. Table 3 provides a comparative overview of the biofortification approaches, highlighting their unique characteristics, advantages, and limitations.

Table 3. Advantages and constraints of transgenic, conventional breeding, and inorganic fertilizer approaches for zinc biofortification.

Consideration	Transgenic Breeding		Conventional Breeding		Agronomic Biofortification	
	Benefit	Limitation	Benefit	Limitation	Benefit	Limitation
Geographical applicability		Works where soils inherently have Zn minerals		Works where the soils are inherently rich in zinc	Works even where soils are Zn-deficient	
Cost of developing technology		Relatively expensive	Relatively cheaper compared to genetic biofortification		Cheaper compared to genetic and conventional breeding	
Application cost	Cheaper		Cheaper			Costly
Acceptability		Mostly not acceptable	Easily acceptable		Easily acceptable	
Farmers' Accessibility Time		Takes several years before a cultivar is developed and assessed		Slower process, requiring multiple generations to achieve significant zinc biofortification	Less time-consuming approach	
Sustainability	Very sustainable, as the same genetic material can be used for years		Sustainable			Not sustainable

The pros and cons of using agronomic and genetic biofortification are summarized in Table 3. In the context of adopting agronomic and genetic biofortification, it is important to realize that farmers cultivate crops for two primary reasons: personal consumption and sale. When farmers are well-informed about the advantages of Zn biofortification, or any biofortification, they might opt to grow biofortified varieties or consider using Zn fertilizer if they are cultivating for home consumption. However, when production is intended for sale, the preference is for a popular biofortified variety in high demand in the market, given that Zn fortifications are not physically detectable or discernible by taste [76]. This lack of physical verification or taste distinction provides little incentive for biofortification, as buyers cannot ascertain whether the crop has been fortified. It is for this reason that in many countries, prices for biofortified varieties are at par with non-biofortified varieties [77,78]. In such a case, farmers are more likely to choose agronomic biofortification if Zn boosts yield or opt for genetic biofortification if the variety has better yield or other superior attributes.

Integrating high-yield potential with improved nutritional quality, especially through conventional breeding methods, poses a significant challenge [79,80]. The complexity arises from Zn concentration in grains, which is a multifaceted polygenic trait with numerous component traits. This complexity is further compounded by the fact that elevating mineral concentrations may sometimes result in a reduction in other desirable traits [81].

Consumer preferences encompass various factors, including safety, taste, visual appeal, and nutritional aspects. Currently, only a limited number of Zn-biofortified varieties have been developed and released [12], leading to a scarcity of choices for consumers. This scarcity may omit traits valued by consumers, such as yield. While there is limited scientific evidence suggesting that foods developed through transgenic biotechnology may have detrimental effects on human health, the majority of criticism revolves around concerns related to the safety and ethics of the approach [82]. In some countries, consumers were only inclined to buy transgenic foods when offered at a discounted price [83]. This underscores the specific value that customers associate with a transgenic crop. In contrast, agronomic biofortification presents a different option. This approach effectively bridges the gap between consumer preferences and the pressing need for improved nutrition. It accommodates consumers' desires for their favored crop varieties while simultaneously addressing the imperative of advancing nutrition, thus providing a promising path toward the wider acceptance and adoption of biofortified crops within agricultural practices.

The cost of implementing agronomic and genetic biofortification can be examined from both research and farmer perspectives. At the research level, genetic biofortification can be expensive compared to agronomic biofortification due to the complex processes involved and the number of years that a single genotype is evaluated before release. Research costs associated with transgenic biofortification, for example, can range from USD 1 million to USD 10 million per variety compared to only USD 50,000 to USD 500,000 per nutrient in agronomic biofortification [84]. A large upfront investment is therefore required for genetic biofortification, but once germplasm has been developed, benefits can be realized across countries with only limited additional costs and very little or even no added cost compared to non-biofortified material on the part of farmers [85].

In contrast, agronomic biofortification differs in that profit-making organizations are generally responsible for producing the essential fertilizers. Consequently, farmers shoulder the overhead costs incurred by the manufacturing companies. This may further be compounded by additional application costs if Zn fertilizers are not integrated with the fertilizers commonly used to enhance crop productivity. In the long term, the utilization of fertilizers for crop biofortification proves to be a costly endeavor. However, multiple studies have highlighted the residual effect of Zn fertilizer in soil for up to 10 years, and that application is not needed every year [86]. This implies that farmers may not need to apply Zn fertilizer to their soil each year if their goal is to biofortify their crops. This approach can be both cost-effective and environmentally conscious, lessening the annual financial burden on farmers and reducing overall fertilizer usage.

Successful breeding programs aimed at biofortifying food crops with Zn are dependent on the availability of Zn in the soil. Genetic biofortification assumes that the soil has sufficient soil Zn for mineral-rich crop growth, as it focuses on enhancing plant absorption, like modifying root architecture [30]. However, nearly 50% of global cereal-growing areas have low plant-available Zn in their soils [45]. In such regions, achieving desired grain Zn accumulation may be unfeasible, necessitating Zn supplementation through fertilizer. In Pakistan, a biofortified Zn wheat variety, Zincol-2016, when grown alongside a reference variety in Zn-deficient soil at two sites, did not show a higher grain Zn concentration compared to the reference variety. Nevertheless, the application of Zn-rich fertilizers resulted in a significant increase in grain Zn concentration for all varieties at all sites [87].

Conversely, soil factors like pH, organic matter, and nutrient concentrations, as well as microbial activity, can hinder Zn availability even in Zn-rich soils [88]. In these cases, relying solely on fertilizer may not be suitable, and farmers can explore alternative agronomic biofortification methods like manure or beneficial microorganism applications to address complex challenges in effective Zn biofortification.

4. Status of Biofortification in Developing Countries: Case of Common Bean in Malawi

Biofortification of common bean in Malawi has progressed from early germplasm releases to broader value-chain integration, though challenges remain in awareness and seed systems (Figure 2). High Fe and Zn bean varieties (e.g., NUA45, NUA59) were first introduced and released in 2009, and additional varieties have been added to the national pipeline, anchoring genetic biofortification efforts. Programmatic scale-up accelerated through partnerships between national research (DARS), HarvestPlus programme, PABRA/CGIAR partners, and donor projects, which have supported seed multiplication, demonstration plots, and incorporation of high Fe and Zn beans into home-grown school feeding and other institutional procurement models [89]. Recent delivery models report hundreds of thousands of households reached with biofortified seeds and significant institutional uptake through school feeding pilots, while aggregated regional initiatives under PABRA/Alliance and partners documented rapid expansion of high-iron bean distribution across several African countries, including Malawi. Remaining barriers to full impact include low consumer and farmer awareness of the nutritional benefits, limited early-generation seed availability, behavior-change needs for utilization, and the need to strengthen commercial seed and processing markets to ensure sustainable demand. Together, these advances show that Malawi has moved from proof-of-concept to scaling, but continued investment in seed systems, demand creation, and institutional procurement is needed to realize the full nutritional impact of biofortified beans nationally. On the other hand, agronomic biofortification is rarely practiced, as most farmers apply manure or mineral fertilizers primarily to boost crop yields rather than to improve grain micronutrient concentrations. The most commonly used fertilizers are NPK formulations such as 23:10:5+6S+1Zn, along with urea and calcium ammonium nitrate (CAN). Even when the NPK formulation contains 1% Zn, the focus remains on yield improvement rather than enhancing grain Zn content. In general, the current status of biofortification in developing countries shows predominant reliance on conventional breeding, with minimal adoption of genetic engineering and omics-based strategies due to technological, regulatory, and infrastructural constraints (Figure 2).

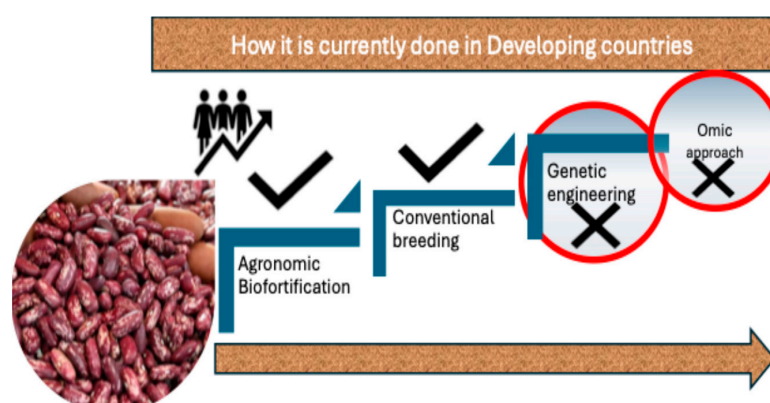


Figure 2. Current status of biofortification approaches in developing countries, showing predominant reliance on conventional breeding, with minimal adoption of genetic engineering and omics-based strategies due to technological, regulatory, and infrastructural constraints.

5. Promising Implementation Strategies to Enhance Biofortification of Common Bean in Developing Countries

Promising implementation strategies to enhance biofortification of common bean in developing countries require a multi-pronged approach that bridges agricultural innovation with nutrition-sensitive interventions (Figure 3). Strengthening the seed supply chain, development and deployment of biofertilizers for Zn biofortification, selecting local germplasm of beans for Zn biofortification, and seed priming, are being proposed as promising and well-suited to developing countries because are low-cost, simple, and effective technique that require minimal infrastructure and equipment.

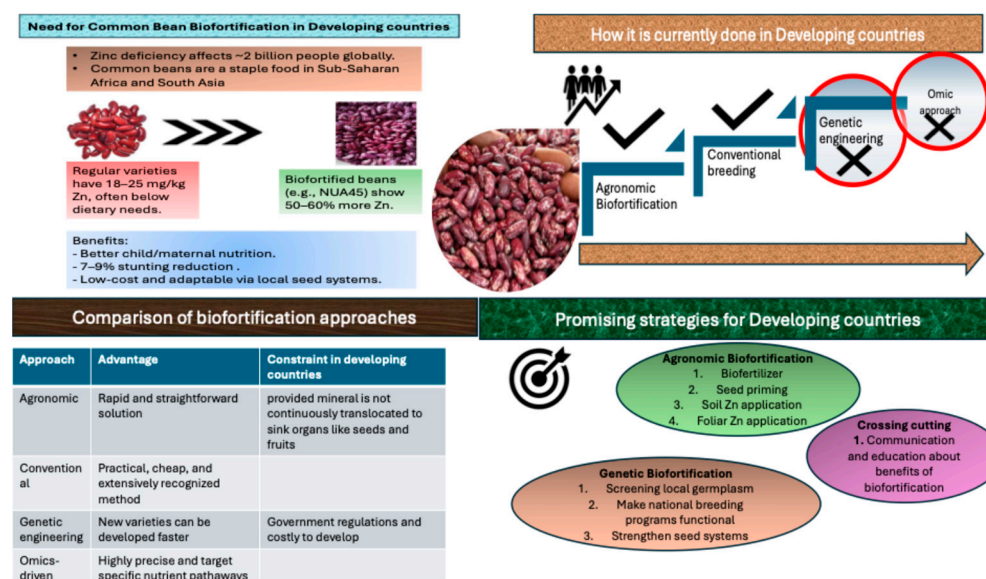


Figure 3. Overview of the need, current status, comparison of approaches, and promising strategies for common bean biofortification in developing countries.

Strengthening the seed supply chain of biofortified seed: The major drawback to the adoption of conventionally bred varieties in developing countries is weak seed systems, especially the lack of early generation seed (EGS). Strengthening early seed generation production is a critical step for scaling biofortification initiatives and ensuring the sustainable delivery of nutrient-rich crop varieties to farming communities. Early generation seed, comprising breeder and foundation seed, forms the backbone of the seed system. However, in many developing countries, production is constrained by inadequate capacity, limited infrastructure, and weak linkages between research institutions and seed multipliers. For biofortified varieties such as zinc-rich common beans, delays or bottlenecks in EGS production lead to shortages of certified seed, slowing adoption rates among farmers. Strategic interventions are needed to enhance EGS systems, including investment in modern seed production facilities, strengthening breeder–foundation seed pipelines, training seed producers on quality standards, and developing public–private partnerships that incentivize commercial seed companies to participate in biofortified seed multiplication. Policy support and targeted funding mechanisms can further stabilize EGS supply, ensuring timely and sufficient availability of planting material to meet growing demand for biofortified crops and, ultimately, improve nutritional outcomes at scale [90,91].

The development and deployment of biofertilizers for Zn biofortification in beans offers a sustainable and cost-effective strategy to address widespread Zn deficiency in both soils and human diets, particularly in low- and middle-income countries. Biofertilizers containing Zn-solubilizing microorganisms, such as certain strains of *Pseudomonas*, *Bacillus*, and arbuscular mycorrhizal fungi, enhance the bioavailability of Zn in the rhizosphere

by converting insoluble Zn compounds into plant-accessible forms and improving root absorption efficiency. When integrated into bean production systems, these microbial inoculants not only contribute to increased Zn content in seeds but also support overall plant growth, yield stability, and soil health. Recent advances in formulation technologies and carrier materials have improved biofertilizer shelf life and field performance, making them more viable for widespread adoption. Successful deployment requires a multi-pronged approach, including the identification of locally adapted microbial strains, rigorous field validation under diverse agroecological conditions, and the establishment of farmer-friendly delivery systems. Linking biofertilizer production with national biofortification programs can accelerate the scaling of Zn-enriched bean varieties, complementing genetic biofortification and contributing to improved nutritional security [92,93].

Selecting local germplasm of beans for Zn biofortification is a crucial first step toward developing varieties that are both nutrient-dense and well adapted to target production environments. Local landraces and farmer-preferred varieties often harbor significant genetic diversity for seed Zn concentration, as well as traits related to stress tolerance, yield stability, and consumer acceptance. Screening such germplasm using high-throughput phenotyping and molecular tools enables breeders to identify promising parental lines that combine elevated Zn levels with desirable agronomic and market attributes. This approach ensures that biofortified varieties retain the cooking quality, taste, and seed color preferred by local communities, thereby increasing adoption potential. Moreover, incorporating locally adapted germplasm into breeding pipelines enhances resilience to biotic and abiotic stresses prevalent in smallholder production systems, reducing reliance on external inputs. Integrating conventional selection with genomic-assisted breeding accelerates the identification and pyramiding of Zn-enhancing alleles, paving the way for more efficient and targeted biofortification programs [94].

Another promising approach is seed priming, which is particularly well-suited to developing countries because it is a low-cost, simple, and effective technique that requires minimal infrastructure and equipment, making it readily accessible to smallholder farmers. Unlike full-field soil or foliar applications, seed priming uses very small quantities of Zn fertilizers or bioinoculants, thereby reducing costs while improving nutrient use efficiency through early uptake and minimizing losses via leaching or soil fixation. The practice accelerates germination and promotes early seedling vigor and establishment, which is especially advantageous in regions with short or erratic growing seasons. Moreover, seed priming can be implemented on-farm using locally available materials, allowing for seamless integration into existing seed systems without the need for specialized services. When integrated with genetic biofortification and complementary agronomic practices, Zn seed priming offers a synergistic pathway to improving both bean productivity and dietary Zn intake in vulnerable populations.

6. Conclusions

Zinc deficiency remains a major nutritional challenge in developing countries, particularly where common beans are a primary food source. Agronomic biofortification offers an immediate, practical, and scalable solution to increase grain Zn concentration, especially in Zn-deficient soils, while genetic approaches have longer-term potential. However, for genetic biofortification to succeed, it must be supported by adequate soil Zn levels, making agronomic interventions an essential precursor. Future research should aim to optimize agronomic biofortification strategies for different agro-ecological conditions, evaluate the cost-effectiveness of locally available Zn sources, and assess long-term impacts on soil health. Integrating agronomic and genetic approaches, alongside understanding

farmer adoption, economic returns, and consumer acceptance, will be critical for scaling up interventions.

Promising implementation strategies to enhance biofortification of common bean in developing countries include strengthening the seed supply chain, development and deployment of biofertilizers for Zn biofortification, selecting local germplasm of beans for Zn biofortification, and seed priming, are being proposed as promising and well-suited to developing countries because are low-cost, simple, and effective technique that require minimal infrastructure and equipment

While the approaches discussed in this review are focused on common beans, their direct applicability to other crops should be interpreted with caution due to species-specific physiological and environmental interactions. Therefore, further research across a wider range of crops and production systems is needed to ensure broad applicability. Strengthening policy frameworks, extension systems, and input delivery chains will ultimately determine the success of these biofortification strategies in combating hidden hunger and improving nutritional security.

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