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Dr. Ayon Alipatra
Department of Agronomy, Dr. Kalam
Agricultural College (Bihar Agricultural
University), Kishanganj, Bihar, India

Dr. Rina Roy
Department of Agronomy, Dr. Kalam
Agricultural College (Bihar Agricultural
University), Kishanganj, Bihar, India

Dr. Adyant Kumar
Department of Agronomy, Dr. Kalam
Agricultural College (Bihar Agricultural
University), Kishanganj, Bihar, India

Dr. Shweta Kumari
Department of Soil Science, Dr. Kalam
Agricultural College (Bihar Agricultural
University), Kishanganj, Bihar, India

Dr. Nagarjun P
Department of Agronomy, Advance
Centre on Sericulture (Bihar
Agricultural University), Kishanganj,
Bihar, India

Devendra Mandal
Department of Agronomy, Nalanda
College of Horticulture (Bihar
Agricultural University), Noorsarai,
Nalanda, Bihar, India

Manish Kumar
Department of Soil Science, Dr. Kalam
Agricultural College (Bihar Agricultural
University), Kishanganj, Bihar, India

Dr. Hena Parveen
Department of Soil Science, Dr. Kalam
Agricultural College (Bihar Agricultural
University), Kishanganj, Bihar, India

Neeraj Joshi
Krishi Vigyan Kendra (ICAR VPKAS),
Bageshwar, Uttarakhand, India

Corresponding Author:
Dr. Rina Roy
Department of Agronomy, Dr.
Kalam Agricultural College (Bihar
Agricultural University),
Kishanganj, Bihar, India

Agronomic biofortification of millets for nutritional security in India: Mechanisms, strategies, and future prospects

Ayon Alipatra, Rina Roy, Adyant Kumar, Shweta Kumari, Nagarjun P, Devendra Mandal, Manish Kumar, Hena Parveen and Neeraj Joshi

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Abstract

The present world's health emergency of hidden hunger, perceived in India as micronutrient malnutrition, faces additional difficulties due to high-yielding modern staple crops which decrease nutrient content. Climate-resilient millets and their nutritional base as nutri-cereals provide an effective genetic solution to fight against the widespread micronutrients (like zinc and iron) deficiencies which exist today. The Indian agricultural systems face challenges ranging from severe soil degradation to abiotic stresses, and thereby limiting their nutritional potential. The combining traditional plant breeding and agronomic practices with biofortification creates a solution that enables farmers to increase their grain nutrient density within a cropping season. The review investigates metal ion uptake mechanisms together with phloem loading processes and seed accumulation methods while assessing field effectiveness of specific agronomic practices which include foliar fertilization, seed nutri-priming, nano-fertilizers and integrated nutrient management (INM). This paper also reviews how different crop varieties respond to various conditions in India's main millet crops which include pearl millet (in arid regions) and finger millet (in lateritic soils) and dual-purpose sorghum. The extensive use of biofortified millets faces three main obstacles viz. ongoing economic expenses that burden resource-limited farmers, the anti-nutritional phytates restricting their nutrient absorption and the lack of premium market prices for the produce. The implementation of biofortification in mainstream fields requires future work to combine site-specific agronomy with post-harvest technology and effective policy measures like micronutrient subsidies and guaranteed procurement.

Keywords: Agronomic biofortification, hidden hunger, millets, zinc and iron deficiency, phytic acid, food security

1. Introduction

1.1 Global and Indian Malnutrition Scenario

Malnutrition has a strong chain & network with socio-economic inequalities at global level, and has become a vicious cycle of poverty and poor health. WHO in key findings of 2020 edition, states that due to undernutrition (in the global context) there is an estimated 144 million children, under the age of five years, experiencing stunting, and about 47 million are subject to wasting. These existential failures are mostly fueled by diets which (though adequate in total energy content), are deficient in required micronutrients and therefore hamper physical development and cognitive development in susceptible groups. The malnutrition problem of the 21st century is subtle, because it's no longer about calory deficiency, but a deficiency in micronutrients, the so-called Hidden Hunger. Hidden hunger, as Rodriguez-Espinosa *et al.* (2024) ^[48] define it, is now impacting large groups of demographics, as more than half of all preschool-aged children, and two-thirds of young women of reproductive age worldwide are affected by it. Lowe (2021) ^[34] further states that this type of malnutrition impacts more than two billion individuals in the world whereby they might be taking enough energy but are not getting the essential vitamins and minerals to ensure optimum growth and development. Such an effect creates a serious paradox in the current food security situation: the Green Revolution was able to produce an effect of increasing the yield of staple crops, but, in turn, it ultimately gave rise to a dilution effect, as the total production of grains increased, which caused a simultaneous decline in their nutrient density (Yilmaz and Yilmaz, 2025) ^[67].

Therefore, the contemporary diets are high-energy and low-nutrition staple foods, which worsens the micronutrient deficiencies despite the high food availability in some regions. To combat this distorted kind of malnutrition, there is need to devise methods that will change the agricultural orientation towards not just raising the volume of harvest but also to include a radical improvement in the nutrient content of food supply.

In the Indian context, undernutrition among children is a serious social health crisis. Even though India has become self-sufficient producing enough grain to meet its demand, the country still is struggling to overcome the nutritional insecurity. Global hunger index (2024) rates India as 105th, implying that level of hunger is serious and the rate of child wasting is quite high in the country. The nutritional deficits have catastrophic effects, as research by Mhamane and Ramanathan (2022)^[37] indicates that malnutrition causes at least 69% of all under-five deaths in the nation. Moreover, they highlight the alarming rates of prevalence of stunting among the children in India being 35.5 percent and wasting being 19.3 percent, which require urgent and scaled nutrition intervention measures. This micronutrient deficiency information is mainly associated with iron and zinc. Recent report by Yadav *et al.* (2024)^[65] based on the Comprehensive National Nutrition Survey indicates that anaemia is a serious issue of social health concern, with 40.5% of children aged 12-60 months are anaemic. The research also points to the direct correlation between the deficiencies of micronutrients and the anthropometric failures, including stunting and wasting, which highlights dire need of uniting the efforts that goes beyond the caloric requirements.

1.2 Millets in Indian Agriculture

To cope with these nutritional deficiencies, the Indian food basket has now been more diversified by the revival of forgotten millets in the diets. In the past, the Indian diet was based on millets and this could be dated back to the Vedic era. Millet is often called the Nutri-cereals, it has always been a constituent component of the Indian agriculture but unfortunately was pushed to the periphery of development in the Green Revolution and gave way to wheat and rice prominently. According to Singh and Thakur (2025)^[53], millets were set aside in the Green Revolution, which strongly promoted the refined grain crops, even though these grains had historically dominated the world. Nevertheless, a paradigm shift, which has been triggered by the growing numbers of non-communicable diseases and nutritional insecurity has set-off a trend that has seen a shift towards mainstreaming or relocation of these traditional grains, bringing them back to their former status as a vital part of a healthy diet. The revival of agriculture became monumental to the world when United Nations announced that 2023 as the International Year of Millets and thereby millets gained popularity among common man in recent years (Panigrahy and Padhi, 2023)^[41]. Harish *et al.* (2024)^[23] explain that this initiative has put forth both large millets like pearl millet, sorghum, and finger millet, and also various minor millets in the limelight in the Asia-Pacific region and India is the major producer of these millets/cereals. This worldwide recognition has given India a multi-level platform to rebrand millets not only as *the poor man's food*, but as climate-resistant nutrient-rich powerhouses with the potential to help in dealing with lifestyle diseases and malnutrition. The rejuvenation of millet crops is critical in transforming the national discourse of food security to sustainable nutritional security (Sahoo and Mahapatra, 2023)^[49]. Compared to normal staples, millets have a higher natural percentage of calcium, iron, and dietary fibre. Although millets

have vast potential in terms of climate resilience and better nutrition, to achieve full potential it is necessary to overcome the current manufacturing constraints as well as to systematically improve their basic nutritional values.

But despite their higher nutritional value, indigenous nutritional value of the millet grains produced on depleted soils is usually not good enough to cover the Recommended Dietary Allowances (RDA) of the vulnerable groups, and hence, other scientific manipulations are needed. The wave created by the International Year of Millets should now be converted into a continuous and practical gain to the agricultural sector. Estimating the post-2023 scenario, Pradhan *et al.* (2025)^[43] mention that the only awareness of consumers is not enough to help Indian farmers, and there is an urgent need to establish accessible and enhanced agronomic practices to make millet farming scientifically stable and an economic choice. And therefore, to guarantee the farmers as main beneficiaries, interventions are needed to bridge the present gap between the modern nutritional needs and the old farming practices.

1.3 The Need for Biofortification

Though breeding of crops has been the main instrument in the process of crop improvement, but genetic enhancement has its own limitations as a method of solving the malnutrition crisis. Modern-day breeding methods have commonly reduced the genetic diversity of crops as a side effect, and no intent to do this, and thus resulting in a founder effect where the natural accumulation of the micronutrients in the grain is limited as demonstrated by Kumar *et al.* (2024)^[31] in their analysis of cereal domestication. Genotype × Environment (G×E) interactions make the breeding programs time-consuming (this sometime takes over a decade to release a commercial variety), and very often constrained by G×E interactions, where nutrient expression depends mainly on the soil type (Bouis *et al.*, 2024)^[10]. Such genetic bottleneck, together with the ten-year development and release of new varieties, highlight the need to complement them with quick-moving measures in bio-fortifying staple crops. Moreover, it is impossible to attain the genetic potential of a crop, when the soil itself is deficient in the required micronutrients to facilitate its absorption.

To avoid the time and restrictions caused by traditional breeding, agronomic biofortification has become the most useful complementary interventions. It is a intentional addition of mineral fertilizers to the soil or to foliage to enhance the nutrient levels of the edible portion of the crops, which is a quick and adaptable solution (Shilpa *et al.*, 2025)^[51]. Also supported by Avnee *et al.* (2023)^[5], this practice can be described as the controlled nutritional intervention that involves the using mineral fertilizer to the soil or by spraying the same on the plant foliage, with the aim of temporarily, but fast, increasing the micronutrient content of the edible portions of the crop. In contrast to this, Genetic strategies require multiple growing seasons and therefore many years to achieve a specific outcome, whereas the process of agronomic biofortification can be conducted in one growing season, providing a quick and highly flexible way to outcome a particular micronutrient deficiency in a selected region. Moreover, recent reviews confirm that agronomic interventions are affordable and complementary to genetic methods. Such practices offer a dual advantage of improving crop yield and nutritional value during climate change (Bhardwaj *et al.*, 2022)^[7].

These agronomic interventions however, do not always work equally and their effectiveness largely depends on G×E interactions. A study by Teklu *et al.* (2023c)^[57] on finger millet

has proven that crop production and sensitivity to zinc and iron fertilization are very variable according to the particular genotype, geographical or even topographical capabilities (such as the slope position). Now this statement underscores the fact that though the use of external fertilizer is effective, it needs to be under strict calibration to the environmental factors of the locality and inherent genetic characteristics of the selected millet variety in order to achieve maximum effectiveness. Agronomic biofortification has huge effects on the final nutritional content of the grain when applied appropriately. In the respective field tests, Teklu *et al.* (2023b) ^[56] gave empirical data that agronomic biofortification of finger millet with zinc and iron can considerably increase the ultimate mineral level of the harvested grain. Teklu *et al.* (2023a) ^[55] emphasize that this method proves especially useful in raising zinc and iron concentrations in grains to provide the rural population with nutrient-rich foods until the long-term breeding programs can be implemented. Their works confirm that planned & calibrated management of fertilizers not only complement the overarching genetic activities but is also a highly successful practice that can be applied independently to provide nutrient-rich millets to the populations with hidden hunger in a very short time period.

2. Micronutrient Status of Indian Soils and Millets

2.1 Soil Profile

The primary limitation to the effectiveness of biofortification is the soil's micronutrient supply, and for much of the arable land in India, the national-level surveillance systems provide significant evidence of this distinct micronutrient deficiency. There has been a comprehensive analysis of over 30 million soil samples, which shows that 39% of soils in India are critical for the availability of soil-zinc for plant uptake (Khokhar *et al.*, 2024) ^[29], and the spatial distribution of these soils is not equal, with Uttar Pradesh reporting 29% of soils having zinc deficiency, in Odisha 48%, and Bihar 67% of soils with zinc deficiency (Khokhar *et al.*, 2024) ^[29].

In addition to zinc deficiencies in Indian soils, there is also a general degradation of soil profile throughout the country for more than one micronutrient, with concurrent zinc, iron, calcium and magnesium deficiencies that adversely affect yield potential of soil and ultimately total crop nutritional value (Shilpa *et al.*, 2025) ^[51]. The problem of micronutrient deficiency is not limited to the actual absence of these nutrients from soils, as many soils that are likely to contain micronutrients have limited solubility and root access because they have one or more of three hurdles (high pH, high electrical conductivity, or low organic matter) which act as barriers to physiological access to the solubility and root access of existing trace-elements in the soil (Sonu *et al.*, 2025) ^[54]. As such, in most of the soils which meet the standard for total mineral content, the micronutrients available for root uptake are restricted only in subsoil, therefore needing targeted agronomic management practices and unique delivery systems to maximize the uptake of these nutrients by roots and avoid nutrient lockout (Bhardwaj *et al.*, 2022) ^[7].

2.2 Native Nutrient Profile of Millets

Millets are, by and large, superior to other cereal grains due to their unique nutritional profile and ability for coping with degraded soils (and sometimes abiotic stresses too). When compared to processed grains (largely wheat and rice), there is a huge inherent genetic difference in the initial concentrations of iron, zinc, and calcium in pearl millet, finger millet, and sorghum (Singh and Thakur, 2025) ^[53]. Studies on the combining abilities of pearl millet germplasm provide confirmation of

large-scale variability in the native profile of millet and an opportunity to improve both the genetic and agronomic qualities of millet (Gaoh *et al.*, 2023) ^[16].

For the expression of the native profile of millet to occur, it is necessary to employ site-specific agronomic practices at the field or site of cultivation. Native mineral concentrations of millet grain are sensitive to aspects of field like slope and location (Teklu *et al.*, 2023c) ^[57]. To sustain and improve the native profile, modern agronomy must incorporate the use of organic soil amendments. Research indicates that combining tillage and integrated nutrient management practices is advantageous to the agronomic performance and nutritional value of minor millets and improves the overall performance and nutritional values of these grain types (Vanathi *et al.*, 2023) ^[62]. Additionally, the use of organic manures (such as farmyard manure, vermicompost), along with iron and zinc supplementation, significantly contribute to increased yield attributes and native grain nutrient density of pearl millet (Chaudhary *et al.*, 2024) ^[12].

2.3 The Dilution Effect in High-Yielding Varieties

Agriculture is rotation of sowing, growth and harvest, but as we produce lots of crops, like wheat or rice, the more we produce the less nutrition our food has. By using various different pesticides or applying numerous types of inorganic fertilizers, a farmer may be successful with some crops to produce more weight than it's normal, but the food/produce will not have the same nutritional value. Crops usually lose many important and essential nutrients (especially micronutrients) after the first few harvest cycles. After the advent of green revolution, most staple food crops (especially wheat and maize) had decreased nutritional quality because they were focused on increasing their biomass. This decrease in nutrition occurs as the yield goes up (*i.e.* Dilution), therefore farmers use different methods to get more yield (external fertilizer application).

Farmers continue to try and get as much yield from their crops as possible (from already exhausted fields), and with such higher yields, the produce lacks many important micronutrients and therefore, the more yield doesn't necessarily mean that it's better. On top of such agronomic dilution effect, climate change may greatly affect crop micronutrient bioavailability (Reboul *et al.*, 2026) ^[46]. Simulated environmental trials provide distinct confirmations that elevated CO₂ levels (which stimulate rapid biomass generation) cause a severe and direct dilution of iron, zinc, and protein concentrations in pearl millet (Govindaraj *et al.*, 2025) ^[20].

3. Mechanisms of Uptake and Translocation (Agronomic Perspective)

3.1 Root Uptake: Soil pH and Organic Matter

In order for agronomic biofortification of millets to be successful, it is important to ensure access of root system of millet plant to available micronutrients in soil. Tjakata and Itanna (2025) ^[58] have outlined soil parameters like pH, cation exchange capacity (CEC), and percent organic matter as key factors determining bioavailability of essential multivalent cations (e.g., Zn²⁺ and Fe²⁺) and how efficiently roots absorb them from soil. In most parts of the world where agricultural soils shows high pH or calcareous nature, cationic precipitates form when these metals precipitate out of soil solution into stable, insoluble metal complexes. This ends up in a large physical barrier to roots and thereby create limited ability for roots to absorb these cations (Silva *et al.*, 2025) ^[52].

In order to overcome this barrier, agronomic management

techniques should be implemented to manipulate the chemical and biological properties of the rhizosphere. Garg *et al.* (2026)^[18] shows that Plant Growth-Promoting Rhizobacteria (PGPR) contribute significantly to lowering the localized rhizosphere pH and increasing the availability of cations by secreting low-molecular-weight organic acids along with root exudates from millet plants. Once these solubilized metals are in the vicinity of root surface, they will be absorbed into physiological cells through the activity of specific, transmembrane transporters present on root epidermis (chiefly, the ZIP (ZRT, IRT-like Protein) and IRT (Iron-Regulated Transporter) family proteins) that are structurally similar to transported proteins of wheat and other cereal plants.

3.2 Phloem Loading: The Pathway from Vegetative Tissues to the Grain

Micronutrients taken up by roots are moved to vegetative tissue through xylem transport, with the major opportunity for biofortification occurring by remobilizing and phloem loading of these minerals during grain-filling. Throughout developmental stages of a crop, soil-to-root uptake continues; however, this generally declines during last developmental stages. Therefore, the grain has high dependency on source-sink translocation of previously stored minerals from older vegetative tissue as source (Teklu *et al.*, 2023a)^[55].

Agronomic methods, and particularly foliar applications using liquid fertilizers and/or sometimes advanced nano-chelates, are basically designed to take advantage of this pathway. Applying fertilizer directly onto leaf surfaces allows the avoidance of roots and soil barriers, and facilitates the direct assimilation of minerals into leaf tissue and subsequent phloem loading (Bhardwaj *et al.*, 2022)^[7]. The movement through source-to-sink pathways is physiologically driven, gene mapping in finger millet having identified key transporter protein families being involved in transporting metal complexes into the phloem and from there into the developing grain endosperms (Chandra *et al.*, 2024)^[11]. Similar physiological pathways and transporters have also been mapped in other staple crops like rice (Zubair *et al.*, 2023)^[68].

3.3 Barriers: Understanding Phytic Acid and Anti-Nutrients

The millet plant's large amounts of zinc and iron do not ensure adequate nutrition due to the existence of internal biochemical barriers to accessing the nutrients in the grain itself. A major barrier is phytic acid (myo-inositol hexakisphosphate), which is the primary storage form of phosphorus in millet (Jacob *et al.*, 2024)^[24]. Phytic acid acts as a potent anti-nutrient in the protein storage vacuoles in the grain. It shows high affinity for multivalent cations (compounds with more than one positively charged ion), and bind very tightly to form insoluble complexes called phytates (Dixit-Bajpai and Ravichandran, 2024)^[13]. These phytate complexes are resistant to enzymatic decomposition in the human intestinal tract and therefore acutely limit the final bioavailability of agriculturally enriched minerals. Consequently, a successful biofortification strategy must be two-pronged. For example, as stated by Ofori *et al.* (2022)^[40] and Kadapa *et al.* (2024)^[27], agronomists and plant breeders must optimize the physiological accumulation of these minerals, but also implement integrated crop management as well as post-harvest processing methods to reduce or manage phytate levels, thereby ensuring that the agronomically enriched micronutrients translate into bioavailable nutrients.

4. Agronomic Strategies for Biofortification

Agronomic biofortification is a solution for instant, flexible, and essential intervention to fight against global hidden hunger, a bridge to fill the gap between soil nutrient depletion and human nutritional requirements (Teklu *et al.*, 2023a)^[55]. Through application of specific fertilization techniques, agronomists are in a position to overcome environmental limitations to directly increase the micronutrient concentration in the edible parts of food crops (Bhardwaj *et al.*, 2022; Praharaj *et al.*, 2021)^[7, 44].

4.1 Method of Application

Soil Application: The conventional method for the correction of systemic micronutrient deficiencies in soils is the application of inorganic micronutrients, specifically Zn and Fe. In addition to promoting the general well-being of crops, the application of micronutrients has other advantages, such as the increase in biomass and yields, particularly in forages such as triticale. However, in the context of grain biofortification, the application has some constraints, particularly in soils characterized by high levels of calcium and alkalinity, where a significant proportion of arable lands in the world is located. This is mainly characterized by the very rapid rate at which applied micronutrients precipitate and get fixed in the soil matrix, thus becoming a barrier for the absorption of the applied micronutrient by the roots and the efficiency of the applied fertilizer, as noted by Matumba *et al.* (2025)^[36] and Silva *et al.* (2025)^[52].

Foliar Application: To avoid the fixation of micronutrients in soil, applied externally, foliar application of these nutrients has become a recognized method to enrich the grains directly with nutrients. Foliar application of micronutrients at critical phenological stages, like booting, flowering, and grain filling, enables cuticular and stomatal uptake of the applied micronutrient into the plant. Application of drone technology for spraying foliage with Zn has shown improved yield and highest quality of cereal grain in terms of micronutrient concentration (Gao *et al.*, 2024)^[15]. Such foliar application of micronutrients causes very rapid remobilization of these nutrients from the source to sink and thereby biofortifying many crops, both root vegetables and cereal grains, that are adversely affected by micronutrient deficiencies.

Seed Priming (Nutri-priming): With the help of seed priming, where seeds are subjected to diluted solutions containing micronutrients before sowing, there is an increase in metabolic efficiency in seedlings. Seed priming can be used in conjugation with other genetic or agronomic methods to make sure that seedlings develop an appropriate structure to combat early nutrient deficiencies (Mallipeddi *et al.*, 2026)^[35].

4.2 Source of Nutrients

Inorganic Fertilizers (Sulfates versus Chelates): The availability and absorption of a non-organic chemical fertilizer will ultimately influence whether or not it's used. Although minerals like Non-organic sulfates have been utilized over time due to their low cost, their fixation into the soil may reduce their long-term functionality as well. However, due to ability of synthetic chelates to prevent the destruction (precipitate, oxidize, or become fixed into unavailable complexes) of metal ions by other soil elements, it remains a highly functional source of iron for biofortification due to its longer solubility compared to cheaper options (Jahan and Tar'an, 2023)^[25].

Nano-fertilizers: The total synthesis of nanoparticles offers a completely new approach towards agronomic biofortification. It has been proven that by using nano fertilizers, like nano-zinc and/or nano-iron, a volumetrically larger amount (higher surface-area-to-volume ratio) is achieved as compared to traditionally sized fertilizers; thereby a controlled rate of absorption is achieved while at the same time enhancing tissue penetration of these fertilizing. It has also been proven that by creating special formulations containing a combination of both Rhizobacteria (PGPR) and zinc or iron nanoparticles, a high degree of precision may be reached while at the same time decreasing environmental contamination that is caused by nutrient running off into water bodies, and also enhancing the quality of nutrients found within the crops harvested (Guardiola-Márquez *et al.*, 2023b)^[22].

4.3 Integrated Nutrient Management (INM)

Impact of FYM and Vermicompost on the Sustainable Biofortification of Crops: For the purpose of sustainable biofortification, it is suggested that an INM approach must be undertaken to avoid (or reduce at least) soil degradation. Organic amendments like Farm Yard Manure and vermicompost improve the physico-chemical properties of the soil and physiological responses of the plants. This will enhance the crop biofortification process (e.g., fine rice varieties; Khan *et al.*, 2023)^[28]. The application of vermicompost tea as a substitute for chemical fertilizers will enhance the yield and nutrient content (grain weight) of the crop. This will develop the concept of sustainable biofortification with reducing the use of chemical fertilizers (Abdel-Lattif and Abbas, 2025)^[1].

The combination of Biofertilizers (e.g., ZSB; Zinc-Solubilizing Bacteria) with Chemical Fertilizers: Potent Zn-Solubilising Bacteria (ZSB) consortia play a role in the mobilization of both indigenous and exogenously applied Zn in the soil through the production of organic acids and siderophores (Upadhayay *et al.*, 2025)^[59], it is also most advanced form of agronomic biofortification. There appears to be a very complicated biological cross-talk between ZSB and the root system of host plants, which impacts nutrient acquisition in a way that results in significant growth enhancements and successful bacterial-assisted biofortification (Ali *et al.*, 2023; Upadhayay *et al.*, 2022)^[60].

The impact of introducing these specific types of PGPRs in the soil in which the crop plants have previously grown can be underlined by seeing the impact of bacteria on the biofortification potential of the crop with regard to the concentration of Zn in the harvested grain under reducing conditions because of soil fertility limitations (Upadhayay *et al.*, 2022a)^[61]. Therefore, to obtain maximum benefit from such type of approach to crop development, new advanced agronomic practices are now shifting the emphasis on inclusion of integrated nutrient management by combining use of both the bio-fertilizer and nano-fertilizer technologies together. With the implementation and application PGPR root inoculations along with nano fertilizer application provide cereal crops with a highly sustainable, synergistic method of achieving biofortification (Jalal *et al.*, 2023)^[26], and therefore open windows of possibilities for millets too. As this approach allows for the combination bio-fertilizer and nano-fertilizer technology, therefore, it will help accomplish simultaneous biofortification of many micronutrients (like Zn and Fe) and biologically active phytochemicals within the same growing season, thereby providing optimal plant nutritional value from the soil to the human food system (Guardiola-Márquez *et al.*, 2023a)^[21].

5. Crop-Specific Review of Literature (Indian Studies)

effectiveness of agronomic biofortification is highly specific for each crop and also is influenced by regional agroclimatic zones. This section reviews some recent field trials and agronomic interventions for major millets in India, with focus on different physiological and geographical aspects of each crop.

5.1 Pearl Millet (Bajra): Arid Zone Agronomy

Pearl millet is more grown in arid and semi-arid areas of north-west India, mostly Rajasthan and Haryana. As a climate-resilient crop, pearl millet is naturally an important source of iron and zinc for people with marginal economic status (Satyavathi *et al.*, 2021)^[50]. However, due to the frequent abiotic stresses that occur in drier regions, availability of nutrient is mostly limited, and such situation calls for effectively designed agronomic interventions.

Recent research through field trials, proved that foliar application of fertilizer has a significant positive effect on pearl millet grain density. These field trials that assessed the effect of foliar application of 0.5% ZnSO₄ and 0.5% FeSO₄, on both the quantity of all grain produced (i.e. yield) and the concentration of zinc and iron in the seed endosperm (Kumar *et al.*, 2021)^[32] and both parameters showed increase in values recorded. Along with this, the results of the studies conducted on practices of moisture conservation, when compared with foliar micronutrient sprays, greatly increase nutrient uptake by pearl millet in arid areas such as Rajasthan, due to the significant amount of fixation that occurs at the soil level alkaline soils of that area (Yadav *et al.*, 2021; Vikramarjun *et al.*, 2025)^[66, 63].

The synergy between agronomic strategies and the use of biofortified genetics is increasing the effectiveness of both. For example, cultivation of Dhanashakti, India's first biofortified pearl millet variety, has demonstrated to have a positive response to integrating agronomic management. Research indicates that Dhanashakti and other biofortified hybrids achieve the full genetic potential for high iron (>70 ppm) and zinc levels, mainly by timely foliar applications and can be helpful in alleviating hidden hunger in both Rajasthan and Maharashtra cities (Kadapa *et al.*, 2024; Shilpa *et al.*, 2025)^[27, 51].

5.2 Finger Millet (Ragi): Calcium and Iron Biofortification

Finger millet is mostly cultivated in the lateritic and red soils of southern India (Karnataka, Tamil Nadu, and Andhra Pradesh), and hold high nutrient density due to its high levels of calcium (about 344 mg per 100 grams), and healthy iron content. To fully utilize its health benefits for child nutrition and public health systems, biofortification of finger millet is need agronomically to match its sink sizes (Boda *et al.*, 2025)^[9]. The results obtained from detailed characterisation of finger millet germplasm at global level showed a great variability in nutrient concentration of grains across the germplasm and therefore, provide an excellent starting point for biofortification (Backiyalakshmi *et al.*, 2024)^[6]. However, to make biofortification of finger millet a successful venture at field level, complete information of local soil conditions is needed. Through recent agronomic advancement in breeding and biofortification, finger millet has adapted to respond very well to the addition of minerals (Teklu *et al.*, 2023c; Patel *et al.*, 2025)^[57, 42].

Field trials to study the effectiveness of biofortifying finger millet, with zinc and iron application either as basal soil application or foliar spray, have been undertaken at some locations in south India. These trials showed that both methods of application were able to significantly increase levels of zinc

and iron in millet grains (Teklu *et al.*, 2023b) [56]. It is important to remember, that the overall success of these biofortification systems can be affected by G×E interactions. Geographic studies also supported the fact that the genotypic response of finger millet crops to biofortification was dependent on the location of the field (and thus its associated crop), slope position and soil type where crop was grown. Therefore, researchers proposed that there is no generic *one size fits all* recommendation for fertilising the soil when growing biofortified crops; the recommendations should be agronomically specific to the choice of location & environmental conditions of that location, and must produce both an increase in the amount of calcium and iron content in the grains in final yield. (Teklu *et al.*, 2023a,c) [55, 57].

5.3 Sorghum (Jowar): Dual-Purpose Biofortification

The sorghum species has both an important agricultural function and a cultural function in India. Sorghum grains are the source of human food, and also provide and high-quality fodder for maintaining livestock in the Deccan Plateau and Central India, therefore, agronomic management for this millet focuses on dual purpose biofortification, by supplementing both the grains and fodder parts with micronutrients. With the previous efforts of various breeding and agronomic programs, many droughts tolerant and high yielding (and also high quality) cultivars of sorghum are available in country at present (Nagesh Kumar *et al.*, 2021) [38].

In recent studies conducted by Nagesh Kumar *et al.* (2023) [39], results have shown that the utilizing targeted biofortification strategies along with scientific agronomic practices can achieve grain yields with better protein content and available mineral content. As sorghum is used for both human food and animal feed application of nitrogen, sulfur, and zinc have positive uplifting effect on both the grains and fodder (leaves) (Bhardwaj *et al.*, 2022) [7]. Many proven studies indicate that applying zinc to standing sorghum crop increase grain weight and protein content along with improvement. Enhancement of crop in both grain yields and fodder production, may provide double benefit to farmer and therefore proves to be very economical viable system of agriculture, which further strengthen agricultural sustainability and nutrition stability.

6. Factors Influencing Effectiveness

Though external fertilizer application to biofortify millet crops successfully agronomically is effective, however many other factors also play important roles for determining overall success of the venture, *per se* environmental conditions (site of application, timing etc) and response of specific cultivars (genetics).

6.1 Timing of Application

Successful loading of micronutrient in the grain after fertilizer application depends on phenological stages of the plant (comparative difference between early vegetative growth and reproductive life cycle like mid-booting to early milking), type of application (foliar or broadcasted). (Augustine and Kalyanasundaram, 2020) [4].

Foliar application of zinc and iron during growth periods (especially reproductive stages) helps in fast absorption (through leaf cuticle) & mobilization of nutrients into grains. This timing helps in bypassing the dilution effect which is often happens on application of nutrients during early vegetative stages, and therefore helps nutrients to directly contribute in increasing nutritional density of the grain as against enhancing vegetative biomass only (Shilpa *et al.*, 2025) [51].

6.2 Environmental Factors

The growth any crop plants (including millets) is highly dependent on availability of nutrients to the roots, which is influenced and environmental conditions, mostly soil moisture conditions. Drought stress affects root growth and decreases mass flow and diffusion of soluble nutrient in soil, and thereby physical barrier in nutrient (uptake iron and zinc) (Garg *et al.*, 2026) [18]. To overcome such environmental limitations, strategic fertilizer application along with soil moisture conservation practices are needed. Field studies indicate that in rainfed conditions, mulching and use of hydrogels (methods of in situ moisture conservation) along with application of micronutrient fertilizers notable increase the yields with higher concentration of nutrient in grains (Yadav *et al.*, 2021) [66]. Another example is application of zinc sulfate as basal fertilizer in pearl millet crop and then its foliar application along with mulching for moisture conservation has helped in mitigating drought induced nutrient uptake barriers and thereby overcome physiological drought tolerance and high concentration of zinc in grains (Vikramarjun *et al.*, 2025) [63].

6.3 Genotype × Environment (G×E) Interaction

The successful increase in micronutrient content in grain by agronomic means is majorly affected by genotype and environment interactions (GXE). Different millet cultivars show different physiological responses to the same amount of fertilizer applied, influenced by their respective agroclimatic zone and locations of planting.

The physical distribution of fertilizer applied and initial (genetic) capacity of cultivars for micronutrient accumulation differs significantly among cultivars due to environmental fluctuations occurring location of crop grown (like soil pH or moisture availability) (Teklu *et al.*, 2023b; Shilpa *et al.*, 2025) [56, 51]. Because of this noticeable variance due to GXE, blanket fertiliser is generally ineffectual over different regions. Therefore, to obtain consistent and scalable feed fortification, agronomic practices must be focused on specific stable, environmentally adapted cultivars which possess high genetic potential for nutrient-dense production in varying agro-ecologies in India.

7. Constraints and Challenges

There are many hurdles and obstacle to implement agronomic biofortification at large scale.

7.1 Economic Viability

For low-resource, marginal farmers it may not be possible monetarily to adopt Agronomic biofortification and therefore, it shows its limited potential in adaptability. On one hand, adapting genetic biofortification is one time investment, in termed of improved seed varieties, and on other side agronomic biofortification require time after time purchase of micronutrients and applying it at various intervals during crop cycle (Bouis *et al.*, 2024) [10]. Therefore, it is important to compare the expense of micro nutrient inputs and their time required application against final economic returns. If a guarantee of net income increase is not promised the it is difficult for small marginal farmers to accept this as mainstream agronomic practice at extra expense (Teklu *et al.*, 2023a) [55]. Moreover, millet grows at many regions in India, perform under economic limitations. As the primary input cost in compare to total market value of final produce in millets will be high, such risk in investing will be difficult to justify along with ongoing soil management practices and therefore, for millet growers it will be difficult to afford this approach (Harish *et al.*, 2024) [23].

7.2 Bioavailability: The Phytate Issue

It is to note that in humans at physiological level, it is difficult to absorbing minerals from millets which are in bound form as phytates (phytic acid) and polyphenols (chelated with divalent cations) and this makes Biofortification of millets a physiological hurdle (Jacob *et al.*, 2024)^[24].

The chelation form insoluble phytate-mineral complexes in the gastrointestinal tract of human gut; therefore, accumulated mineral will not be able to turn in bioavailable minerals until ow phytate accessions are also introduced (Reddy *et al.*, 2022)^[47]. Post-harvest processing methods like repeated milling and decortication lead to loss of nutrient from grains (zinc/ iron) and retain anti-nutrient materials, thereby gains made from field efforts are lost (Krishnan and Meera, 2022)^[30].

7.3 Adoption: Lack of Incentive in Indian Mandis

Market failures and insufficient financial incentives undermine the implementation of agronomically biofortified food products in the marketplace and on the supply chain. A significant challenge to this is that required nutritional characteristics are generally invisible to consumers; for example, consumers are unable to distinguish between a zinc- or iron-enriched millet grain from a normal, nutrient-poor grain merely on visual characteristics (Foley *et al.*, 2021)^[14]. Traditional agricultural markets (Mandis) are based on physical characteristics of grains like weight and total quantity, and thereby prevent farmers from getting higher prices for their high-value, nutrient-dense produce.

Adding to this concern is the lack of affordable and rapid diagnostic methods at local grain procurement sites that would allow buyers or consumers to test for required micronutrient levels and thus compensate farmers accordingly (Birol & Bouis, 2023)^[8]. Farmers therefore tend to opt for medium to long-term yielding traditional varieties (with high volume and weight) that assure them better returns. To promote and facilitate the adoption and acceptance of biofortified grains policy interventions must be implemented/ and revised in form of MSP for such advanced/ nutrient rich grains and also including these products in PDS to make sure for a guaranteed procurement and production incentive (Singh & Thakur 2025)^[53].

8. Future Perspectives & Recommendations

To undertake a multi-dimensional approach which can support transition of Agronomic Biofortification of Millets from its present early acceptance stages is need of the hour. To undertake this approach specified policy framework, focused long term research and bridge to connect field agronomy to post harvest technology must be implemented.

8.1 Policy: Inclusion of Agronomic Biofortification in Government Subsidies

Lack of structured policy is one of the major factors that stops successful adoption of Agronomic Biofortification mainly by small farmers. Another important factor is high cost for micronutrient fertilizers available in market, which need to be purchased in every cropping cycle and thus add to overall cost, which makes these recurring expenses as one of leading cause adding to inability to use of Biofortified Staple Crops (Garg *et al.*, 2018; Praharaj *et al.*, 2021)^[18, 44]. These issues must be considered with new lens of Government policy and required amendments to be made in already existing ones for must be formulated for Fertilizer Subsidy programs. Formulation like zinc-coated urea or specific customized consortia may be

provided with subsidies, which will reduce the economic burdens associated with millet cultivation. Inclusion of millets in PDS and Mid-Day Meal Scheme will also help to procure biofortified millets and establishing the supply chain for high quality nutrient rich grains to reach the neediest population Restructuring agricultural markets with new systems & metrics, which are farmer oriented, will help in adopting the new cultivars and agronomic practices.

8.2 Research Gaps: Need for Long-Term Residual Effect Studies

The studies available on soil application or foliar spray with micronutrients are available for single crop cycle, and there is research gap that exist advocating practicality and sustainability of these new agronomic practices over a longer time period/ multiple crop cycle and total overall impact in agricultural systems Therefore, an urgent need for longer-term studies that can demonstrate the residual effect of multi-application of micronutrient in complex millet cropping systems (Shilpa *et al.*, 2025; Teklu *et al.*, 2023a)^[51, 55]. The application of inorganic micronutrients opens the possibility to impact soils physical properties and interaction with other heavy metals or antagonistic interaction with important macronutrients (like phosphorus-related zinc deficiency) (Bhardwaj *et al.*, 2022)^[7]. Research focus on residual effect of applied fertilizers and its impact on soil microbiology will provide needed information for maintaining the effective PGPR population, which contribute in maintaining the solubility and availability of essential micronutrients under various stress conditions and upcoming crop rotations. This will help in guiding to establish sustainable and low-input biofortification systems for Indian soil types (Rana *et al.*, 2015; Upadhayay *et al.*, 2022)^[45, 60].

8.3 Processing: Linking Agronomy to Post-Harvest Processing

Post-harvest food processing is like one of the least focused aspects in the chain, and have received less attention than required. Though with the help of agronomic interventions in biofortification, total mineral amount in grains has been increased but most of the processing methods like sequential milling, polishing, or decortication remove the top layer & outer layer of bran (highly nutritious portions of the seed).

Krishnan and Meera (2022)^[30], in their studies stated that during milling process in pearl millets, approx. 50% of the bioavailable iron and zinc become lost. Due to this, the additional mineral content that was generated by costly extra fertilization may get negated by losses due to milling process. Therefore, new approaches are needed to be explored whether fertilizer application timing or more penetrative nano formulations can achieve better results in deeper placements of micronutrients within the endosperms of grains, and thereby reducing mineral loss during milling processes.

Moreover, enhancing mineral quantity in grains alone don't promise to ensure that nutrients will be available for uptake by consumer. Therefore, integrating agronomically advanced millet cultivars with post-harvest processes (like malting, soaking, and fermentation) and breeding research like for low-phytate varieties or high phytate degrading enzymes will allow for more seed to plate flow of nutrients. This, therefore, will be best possible way to achieve smooth flow of mineral nutrients from agronomically fortified grains to diet with maximum absorption and health benefits (Anitha *et al.*, 2021; Reddy *et al.*, 2022)^[3, 47].

9. Conclusion

The widespread problem of hidden hunger (due to micronutrient deficiency) immediate agricultural interventions. Opting climate resilient and nutritional superior millets makes a strong genetic foundation for combating these common deficiencies, mostly due to zinc and iron. The availability of high yield varieties (HYVs) developed through conventional breeding methods, with early anticipated yields, now being proven unsustainable within the current timeline of development in some locations and for particular crops. Therefore, to complement traditional breeding methods, new agronomic biofortification methods are enabling a rapid and flexible approach to enhance nutrient density in millet grains, within a single crop cycle.

The physiological benefits have been accepted for major millet in cultivation (like pearl millet, finger millet, sorghum), however, economic hurdles are there for marginal farmers (e.g cost of biofortification inputs), also the challenges of maintaining phytate levels within normal range through conventional agricultural practice. To realize the full potential of biofortified millet crops, it is critical to create innovative agricultural policies for general public especially marginalised farmers, like subsidies micronutrient input and provisions for guaranteed procurement of fortified millets at premium prices through food security programs. Reducing this gap between soil health and new scientific crop management with systemic market reforms along with agronomic biofortification can assure for nutritional security of Indian agriculture in combating hidden hunger by delivering nutrient rich food.

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