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Agronomic Biofortification in Millets-key to Nutritional Security: A Review

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ABSTRACT

Malnutrition and undernourishment are the major health problems in India with 16 per cent of the population are undernourished and 53 per cent of the women being anaemic. The millet grains called 'nutricereals' are best alternative to address the nutritional deficiencies such as iron, protein, calcium and magnesium prevalent among population. Millets are drought tolerant, photo-insensitive and highly climate resilient crops. Henceforth, Millets are increasingly becoming an alternative source of food, both worldwide and in India. While there has been recent attention on using micronutrient supplements and fortifying foods industrially to assist vulnerable populations, the enduring and environmentally sound effects can truly be realized through fortifying crops with micronutrients during their production stage. Biofortification involves enhancing the levels vital nutrients in the edible portions of crop plants by either modifying agricultural practices or selecting plants improved genetic traits. Agronomic biofortification is an easiest short-term approach for biofortification. It involves the use of fertilizers enriched with micronutrients, which is a straightforward method to improve the nutritional quality of crops. Consuming such fortified crops can lead to improvements in human nutritional status. India is the leading millet producer with 80 per cent of Asia's share making 20 per cent of the global production. Millets, which were long thought of as poor man's diet, are now quickly becoming included in the food baskets of the wealthy as well as a natural remedy for health. The micronutrient content in millets can be explored by various agronomic biofortification methods. These include soil application of micronutrient enriched fertilizers for plant uptake, foliar application of fertilizer, seed primingand soilless cultivation, which are the primary techniques.

Key words: Biofortification, Foliar nutrition, Malnutrition, Millet, Seed priming, Soilless cultivation.

Malnutrition and undernourishment are significant issues in India, contributing to nearly 45 per cent of deaths among children under five. The situation is particularly severe in South east Asia, where 30.1 per cent of children under five are stunted and 14.5 per cent are wasted, compared to global rates of 22 per cent and 6.7 per cent, respectively (WHO, 2022). In Indian scenario, a significant proportion of children under five years old, pregnant women, adolescent girls and lactating mothers in both urban and rural areas are affected by malnutrition (Narayan *et al.,* 2019). While malnutrition is mainly due to inadequate intake of vegetables, fruits, animal-based foodsand other nutrient-dense foods, many impoverished people worldwide are not able to afford these items and instead rely on cereals and affordable staple foods. The need for cereals as both food and animal feed is growing due to population surges in developing nations and shortages in cereal production across several developed countries. Hence, to address the longstanding issue of food insecurity and malnutrition, it's crucial to prioritize dietary quality. As a result, millets are emerged as a substitute food source for people both in India and throughout the world (Kumar *et al.,* 2020).

Of the several micronutrients, deficiencies in zinc (Zn) and iron (Fe) in food crops are well-researched issues that lead to a decline in agricultural output and nutritional quality. The issue of multi-micronutrient deficiencies in Indian soils is evident, with 6.29 per cent of soils deficient in both Zn and Fe. Maharashtra reports the highest extent of deficiency at 12.32% (Shukla *et al.,* 2014). In India, about half of its soils are deficient in available Zn (Praharaj *et al.,* 2016) and the range of Zn deficiency varying from 24% in Gujarat to 86% in Maharashtra (Shukla and Behera, 2011). In the case of Fe, 12.1% soils are reported to be Fe-deficient in India (Shukla *et al.,* 2014). Western parts of the country, mainly Rajasthan, Gujarat and Maharashtra are facing severe Fe deficiency problems (Shukla *et al.,* 2018). These deficiencies impact over two billion people globally, primarily in low- and middle-income nations. More than one-third of people worldwide suffer from zinc deficiency. Children who lack Zn are more susceptible to pneumonia, diarrhoea, deathand stunting. Maternal and child mortality

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can be directly attributed to severe anaemia caused by Fe shortage.

Micronutrient rich staple foods have potential to tackle micronutrient deficiency and offer a stable solution to nutrition related health problems (Welch, 2002). Different approaches have been put forward at the forefront to tackle hidden hunger, such as dietary diversification, pharmaceutical supplementation and industrial fortification. Although there has been a recent emphasis on industrial food fortification and micronutrient supplements to target the weaker section of the society, the only way to create long-term and sustainable impacts is through vitamin fortification during the crop production stage. Fortification involves increasing the nutrient content of food through physical methods like adding salts, while biofortification involves the enhancement of the bioavailable micronutrient levels in crops using techniques such as traditional breeding, genetic modificationand agronomic practices (FAO, 2017). The worldwide health emergency triggered by the COVID-19 pandemic has redirected focus towards the nutritional content of food, especially micronutrients crucial for strengthening immunity. Throughout this time, there was a surge in mineral micronutrient supplementation, highlighting the recognized significance of biofortification in crop cultivation.

Biofortification

Biofortification is described as the method of enhancing the levels of vital elements in the edible parts of plants either through agronomic practices or genetic selection (White and Broadley, 2005). This entails enhancing the micronutrient concentration in a target crop to improve its nutritional quality without compromising important agronomic traits, *i.e.*, yield, resistance to pest and drought etc. Biofortifying crops and increasing the availability of nutrients in their edible parts can aid in preventing micronutrient deficiencies. This involves enhancing the dietary value of a specific plant by increasing its micronutrient content while maintaining its agronomic attributes like yield, pest resistanceand drought resistance. Biofortifying crops and improving the nutrient bioavailability in the edible parts can help prevent micronutrient deficiencies.

The three main strategies under biofortification are transgenic, conventional and agronomic approaches. Conventional biofortification involves selecting high-yielding crop varieties with naturally higher nutrient content and crossbreeding them to develop staple crops with desired nutrient content and agronomic character. Transgenic biofortification involves genetically modifying plants to improve the micronutrients in their edible parts. Agronomic biofortification, a non-genetic approach, focuses on enhancing micronutrient levels in food plants and is often considered more efficient (Dhaliwal *et al.,* 2022).

Biofortification primarily targets staple crops such as cereals, millets and legumes. These crops are starchy and form the main part of diets worldwide, mainly among populations susceptible to micronutrient deficiencies. Biofortification provides a practical way to reach malnourished people who have restricted access to varied diets, supplementsand commercially enriched foods (Saltzman *et al.,* 2013).

Need for biofortification

Our bodies need minute quantities of micronutrients mineralsand vitamins. However, they play significant roles and their deficiencies causes serious health problems such as chronic diseases and stunting, weakened reproductive and immunological systemsand an overall decline in our mental and physical capabilities (WHO, 2022). Among the significant health concerns worldwide, deficiencies in Zn and Fe affect a considerable portion of the population (White and Broadley, 2005). The prevalence of Zn deficiencies in Indian soils (Shukla and Behera, 2012) and the oxidized form of Fe in arable soils, combined with high-yielding varieties, multiple cropping systemsand rising soil degradation, have exacerbated micronutrient deficiencies in India. Given the disparity in nutrition supply versus population needs, inequities in distribution, differences in micronutrient bioavailability from foodand limited access to biofortified foods, it is crucial to add micronutrients like Zn and Fe to commonly consumed food items to increase their concentrations. Addressing Zn and Fe deficiencies in humans through biofortification involves a continuous process that spans soil concentration, plant uptake, accumulation in edible partsand bioavailability in the human body (Shahane and Shivay, 2022).

In the past, pharmaceutical supplementation and industrial fortification have been primary methods for addressing nutritional issues. However, these approaches often have limited reach in low-income countries, where there can be reluctance to take supplements or fortified products in tablet form. As a result, the effectiveness of these strategies is diminished. Therefore, biofortification has been introduced as a novel approach. Moreover, biofortification offers a feasible solution for impoverished rural populations who may lack access to commercially fortified foods and supplements.

Agronomic biofortification

Agronomic biofortification is considered as a near- term technique and also a quickest way for biofortification. It involves the use of micronutrient fortified fertilizersand it's a straightforward way to increase the nutritional quality of the crops (Cakmak and Kutman, 2017). In the present scenario, where the goal is to feed about seven billion people with higher yields, the emphasis is not just boosting production with limited resources, but also on enriching the edible parts of plants with micronutrients to promote good health (Graham *et al.,* 2007). Micronutrients are typically absorbed from the soil and are present in varying quantities in different plant parts. Applying micronutrients as fertilizers can enhance the micronutrient status in the soil and address deficiencies in plants and humans.

Agronomic biofortification offers a key advantage over other biofortification in that the types of fertilizers and their application methods are nonspecific to crop. This means that fertilizer dosageand methods can be easily adjusted from a crop to another. In contrast, other biofortification techniques are specific to certain crops, making it a time-consuming and resource-intensive process to include additional crops in the biofortified profile (Bhardwaj *et al.,* 2022).

Agronomic biofortification involves enhancing the nutrients, vitaminsand mineral content of crops through specific agronomic practices. It serves as an effective method for supplementing micronutrient powders and improving dietary diversity.

Millets as candidate crops for biofortification

Millets are often referred to as “nutria-cereals”, due to its nutritional superiority over riceand wheat, serving as a good source of vitamins, dietary fiber, protein, minerals, essential amino acids and energy. They stand out from other cereals due to their unique morphological, physiological, biochemicaland molecular characteristics, which give them the ability to tolerate and resist environmental stress. India is the primary producer of millet, contributing approximately 80% of Asia’s and 20% of the world’s production (FAO, 2021). Total of around 16.9 million tonnes (mt) grains from an area of nearly 12.7 million hectares (mha), representing about 6 per cent of the nation’s total food grain basket. The primary millet-producing states in India are Rajasthan, Maharashtra, Uttar Pradesh, Karnataka, Madhya Pradesh, Gujarat, Tamil Nadu, Haryanaandhra Pradeshand Uttarakhand. These ten states together contributed approximately 98 per cent of India’s millet production during 2020-21 period, with Rajasthan alone contributing 28.61 per cent of the overall millet production (APEDA, 2023).

India cultivates various kinds of millets, like Pearl millet, Finger millet, Sorghum, Foxtail millet, Kodo millet, Barnyard millet, Little millet, Proso millet and Pseudo millets (APEDA, 2023). Pearl millet is grown in about 7.4 mha, producing 10.1 mt, followed by sorghum (4.35 mha, yielding 4.63 mt), finger millet (1.1 mha, yielding 1.58 mt) and other millets (0.44 mha, yielding 0.35 mt). Pearl millet, finger millet and sorghum make up over 95% of the millet cultivation area, whereas small millets, including foxtail millet, little millet, barnyard millet, kodo milletand proso millet, represent less than 5% of the total cultivated area. (DAC and FW, 2023).

Millets are gaining popularity for their nutritional value as meals that enhances immunity. Millets, which were long thought of as poor man’s diet, are now quickly becoming included in the food baskets of the wealthy as well as a natural remedy for health (Kumar *et al.,* 2016). Additionally, millets are highly climate resilient crops, with early maturity (65-85 days); drought tolerant (150-500 mm rainfall)and the ability to thrive in salinity. Species that best adapt to the specific conditions of an ecosystem and environmental factors will produce the most viable offspring (Ameena *et al.,* 2024a). They can withstand high temperature (>42°C of air temperature) and are well-suited to adverse, marginal and changing environments and work well as intercrop in coconut gardens. However, for achieving maximum yield under low-light conditions in intercropping, varietal selection is crucial as different varieties exhibit varied morpho-physiological responses and yield outcomes when exposed to shading stress (Pooja *et al.,* 2023a). While millets have a rich heritage and pride in India, there has been a greater emphasis on increasing the production of rice, wheatand maize since the Green Revolution. As a result, millets were somewhat neglected. However, in recent years, millets have regained recognition and pride due to their nutritional value and resilience in ecological conditions (Maitra, 2020).

Significance of millets in biofortification

Millets exhibit greater genetic diversity in essential mineral elements such as Fe, Zn and calcium compared to other cereal crops. They are also resilient to diseases and pests, drought-tolerant and serve as reliable crop insurance in developing countries. Unfavorable climate shifts can result in crop failures, leading to food shortages and subsequent malnutrition. Crop productivity is largely influenced by the cultivation practices as these methods impact factors like soil health, nutrient availabilityand water management, which are essential for optimal growth and yield (Ameena *et al.,* 2024b). Given that millets are highly resilient to such conditions, biofortifying millets could more effectively combat malnutrition compared to other grains. In comparison to the recommended dietary intake, low-income rural families in millet-growing areas consume fewer micronutrients. A major contribution to the global fight against micronutrient deficiency and human health might be made by any improvement in millets quality. Reducing micronutrient deficiencies in underdeveloped nations is a major potential benefit of biofortified millets. There has not been much progress made in biofortifying millets. But, over 50 per cent increase in the nutrient content was observed in biofortified varieties while comparing with other normally grown varieties. Even with millets high nutritious content, more must be produced with quality added inorder to move billions of people from nutrient deficiency to nutrient adequacy.

Details of nutritional composition of millets are given in Table 1. Comparison of nutrients in biofortified varieties and popular varieties of millets is given in Table 2. Also, nutrient composition of non-biofortified and biofortified cultivars of pearl millet is detailed in Table 3.

Application techniques in agronomic biofortification

Several factors such as the source and amount of fertilizer, the method of application (whether soil and foliar), the time of fertilizer application and the impact of addition on other minerals have influenced the degree of biofortification (Singh and Prasad, 2014). Numerous agronomic

Table 1: Dietary composition of millets (per 100 g).

Crop	Carbohydrate (g)	Protein (g)	Fat (g)	P (mg)	Ca (mg)	Zn (mg)	Fe (mg)
Pearl millet	67.5	11.6	5.0	296	42	3.10	10.3
Sorghum	72.6	10.4	1.9	222	25	3.01	5.29
Finger millet	72.0	7.3	1.3	283	344	36.6	4.27
Foxtail millet	60.9	12.3	4.3	290	31	60.6	3.5
Proso millet	70.4	12.5	1.1	206	14	4.3	2.2
Little millet	75.7	8.7	5.3	220	17	3.5	9.3
Kodo millet	65.9	8.3	1.4	188	27	32.7	3.17
Barnyard millet	74.3	11.6	5.8	121	14	57.45	17.47

Source: National Academy of Agricultural Sciences, New Delhi (2018).

Table 2: Comparison of nutrients in biofortified varieties and popular varieties of millets **(**Yadava *et al.,* 2017).

Crop	Variety/Hybrid	Biofortified varieties		Popular varieties	
		Fe (ppm)	Zn (ppm)	Fe (ppm)	Zn (ppm)
Pearl millet	HHB 299	73	41	45-50	30-35
	AHB 1200Fe	73	-	45-50	-
	AHB 1269Fe	91	43	45-50	30-35
	ABV 04	70	63	45-50	30-35
	Phule Mahashakti	87	41	45-50	30-35
	RHB 233	83	46	45-50	30-35
	RHB 234	84	46	45-50	30-35
	HHB 311	83	-	45-50	-
Finger millet	VR 929 (Vegavathi)	131.8	-	25	-
	CFMV1 (Indravati)	58	44	25	16
	CFMV 2	39	25	25	16
Little millet	CLMV1	59	35	25	20

Table 3: Mineral composition of non-biofortified and biofortified cultivars of pearl millet (Samtiya *et al.,* 2023).

Pearl millet varieties	Fe (mg/kg)	Zn (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Na (mg/kg)	K (mg/kg)	Mn (mg/kg)
Non-biofortified cultivars							
HC-20	47.10	52.80	434.1	1330	749.9	3712	11.10
HC-10	54.88	38.37	464	1223	767.4	3183	6.69
Biofortified cultivars							
HHB-299	77.71	50.76	436	1462	911.6	4210	8.02
HHB-311	87.79	55.05	564	1035	606	2757	9.78
AHB-1200	67.53	51.77	692.7	1419	574.9	4247	11.18
RHB-233	73.54	52.47	404	1704	874.7	3642	11.79
Dhanashakti	84.26	52.43	919.1	1716	793	5205	12.45

biofortification methods have been evaluated for their efficacy globally. Among these, key techniques include basal application of micronutrient fertilizer for plant nutrient uptake, foliar spraying of fertilizer, seed primingand soilless cultivation.

Soil application

Fertilizers or similar fortifying substances are incorporated into the soil for subsequent absorption by plant roots and translocated to tissues within the plants. Soil micronutrient application aids in replenishing these elements in soil where crops are cultivated, representing a conventional and widely employed method. Studies indicated that combination of soil application and foliar application is highly effective and beneficial for increasing grain production than using either foliar or soil application alone (Ashish *et al.,* 2023). While soil application is widely used for applying micronutrients to crops, it has primarily been evaluated for its impact on improving crop production rather than biofortification. This method is characterized by reduced micronutrient use efficiency, limited cost-effective, soil pollution from the excessive accumulation of unused micronutrients over timeand challenges in achieving uniform distribution across the soil (Bhardwaj *et al.,* 2022).

Maganur and Kubsad, (2020) studied the influence of Zn and Fe enriched organics in kharif sorghum was evaluated during kharif season and represented that the applying 15.00 kg ha^{-1} each of $ZnSO_4$ + $FeSO_4$ to the soil, enriched with farmyard manure (FYM) recorded significantly higher Fe and Zn content in grain as compared to other treatments.

Foliar application

Foliar application means a rapid correction of nutrient deficiencies as well as physiological disorders in crop plants. Nutrient absorption occurs through both the stomata and the epidermis of the plants. Foliar feeding has been shown to be more efficient than soil applications in utilizing nutrients effectively and reducing visual and soil deficiency problems quickly. Pooja *et al*. (2023b) reported improved yield with foliar nutrition using the readily soluble fertilizer, 19:19:19 at 1%, due to the increased nutrient availability from the fertilizer applied as foliar spray. Compared to soil application, foliar application is preferable due to minimal loss of micronutrients. It requires less fertilizer, reduces soil toxicityand allows for direct absorption of micronutrients by plant tissues. Foliar nutrient application ensured timely nutrient availability, offering an effective and economical solution for nutrient absorption, especially in rainfed farming with inconsistent moisture levels (Pooja and Ameena, 2021).

Zou *et al*. (2012) identified that foliar application of Zn was more advanced in enhancing Zn content in grain. Foliar treatment is considered a significant method for representing micronutrient deficiency in arid and semi-arid region grown crops, in which soil-applied fertilizer solubilization and availability of water for irrigation are limited (Chapagain and Wiesman, 2004).

Kumar *et al*. (2020) studied that effect of different sources of Zn and Fe on grain quality and yieldand nutrient uptake of finger millet (*Eleusine coracana* L.). The result indicated that RDF + Zn humate @ 0.25% foliar spray shows significantly higher Zn uptake and RDF + $FeSO_4$ @ 0.5% foliar spray shows higher Fe uptake in grain as compared to other treatments.

Selenium (Se) is a vital micronutrient for humans and animals in small quantities. Inadequate dietary intake is linked to various health issues, including oxidative stress-related problems, decreased fertility, dysfunction of immune systemand a higher risk for cancers (Broadley *et al.,* 2006). Therefore, ensuring an adequate dietary Se intake is essential for human health. Ning *et al.* (2016) examined the possibility of enhancing Se and yellow pigment (YP) in foxtail millet grain through Se foliar application. They evaluated the impact of spraying sodium selenite on the leaves of foxtail millet on yield, Se absorption and accumulation, total protein concentrationand micronutrient content in the grain. The application of Se substantially boosted its accumulation in foxtail millet grain. Across all sites, there was almost a linear relationship between the Se concentration in the grain and the amount of sodium selenite application. Additionally, the total yellow pigment (YP) concentration in grain significantly rose with higher Se rates. They concluded that the foliar spraying of Se effectively and reliably increased the content of Se in grain without any adverse effects on yield or Cu, Mn, Znand Fe concentrations. Moreover, foliar Se application notably boosted the total YP concentration in foxtail millet grain.

Seed priming

Seed priming with nutrients considerably increased the concentration of nutrients in the primed seeds. Seed priming, or nutri-priming, involves soaking seeds in a nutrient solution before planting. This technique can effectively fulfill the early nutritional requirements of crops and ultimately enhance the final yield. Micronutrient seed priming is a cost-effective and environment friendly method that leads to enhanced micronutrient content and increased yield. The success of seed priming depends on crop species, concentration of solution and duration of priming and the benefits include economic effectiveness and the requirement for micronutrients in small amount (Farooq *et al.,* 2012).

Dholariya *et al.* (2020) found that treating finger millet seeds with 30% ZnO at a rate of 10 ml/kg seed, combined with root dipping in 0.5% $ZnSO_4$, along with the recommended fertilizer dose (40:20:0 kg/ha), leads to higher crop yields and improved nutritional content. Foliar application of $ZnSO_4$ @ 0.5% at 60 and 80 DAS led to notably higher Zn content in both grain and straw compared to other treatments. Similarly, using 30% ZnO @10 ml kg^{-1} seed along with root dipping @ 0.5% $ZnSO_4$, resulted in significantly increased Zn uptake both in grain and straw of finger millet. Gajalakshmi *et al.* (2022) studied that how different amounts and types of Zn used in seed priming affect the sprouting and seedling emergence of barnyard millet. It was found that the highest Zn content was linked by the seed priming of 0.50% $ZnSO_4$, followed by 0.25% $ZnSO_4$ and 0.50% Zn EDTA as compared to unprimed seeds.

Soilless cultivation

Soilless cultivation offers a hopeful prospect for agriculture, particularly in areas where soil degradation and scarce water resources are prevalent. This modern cultivation method involves using inert inorganic, organic, or liquid media with specific nutrient concentrations to provide plants with the necessary nutrients. Soilless cultivation of plants is becoming increasingly important in human nutrition, particularly with microgreens, in which the micronutrients are added through media rich in these nutrients (Rouphael and Kyriacou, 2018). Different soilless systems, such as hydroponic, aeroponic, aquaponicsand more, are available depending on crop type and requirements (Bhardwaj *et al.,* 2022).

Hydroponics stands out as the most widely used technique among these methods. They have long been considered as a solution to the urgent need for increased food production to accommodate a growing global population. Since they facilitate the management of plant nutrition throughout their growth by effectively regulating the supply of both water and nutrients. It offers several benefits, such as the ability to monitor nutrient concentrations, ensuring plants acquire nutrients optimally without causing nutritional imbalances (Sambo *et al.,* 2019). In addition to assisting in the effective use of natural resources and boosting food production, which helps to reduce malnutrition, this system helps to address the challenges posed by climate change and abnormal weather patterns.

Akbar *et al.* (2018) found that that applying exogenous calcium (Ca) increased the calcium content in finger millet genotypes. Impact of various concentrations of exogenous Ca in the form of calcium nitrate were determined in grains of two contrasting genotypes of finger millet - GP-1 (low Ca) and GP-45 (high Ca). The results indicated that exogenous Ca directly influenced the accumulation of Ca in grains up to certain point. However, higher or toxic conditions can trigger the plant molecular mechanisms that enhance efficiency and threshold potential. The maximum threshold potential in Ca levels occurred in seeds supplied with an exogenous Ca of 10 mM concentration in both the genotypes. However, this potential decreased when the supplied Ca reached 20 mM (considered toxic) in both the genotypes.

Combination of different application techniques

Sharanappa *et al.* (2019) studied the impact of agronomic biofortification using Fe and Zn on quality and yield of pearl millet [*Pennisetum glaucum* (L.)] genotypes. Study aimed to assess and analyze pearl millet through agronomic biofortification to enhance both grain quality and yield parameters. Among the genotypes studied, G3: HFeZn-113 (high in Zn and Fe) recorded higher Zn and Fe content. Regarding micronutrient applications, applying $ZnSO_4$ to the soil @ 15 kg ha^{-1} and $FeSO_4$ @ 10 kg ha^{-1} along with foliar application of 0.5 % $ZnSO_4$ and $FeSO_4$ each, significantly increased Zn and Fe content.

Reddy *et al.* (2021) assessed the impact of biofortified Zn in pearl millet. Among the various Zn biofortification treatments highest Zn uptake was recorded in the treatment comprising RDF (60:30:20 kg ha^{-1} N, P_2O_5 and K_2O) + enriched vermicompost $ZnSO_4$ @25 kg ha^{-1} along with foliar spray of 0.5% $ZnSO_4$ (at tillering, heading and milking stages) compared to all other treatments. The increased Zn uptake associated with this treatment could be credited to the greater availability of Zn due to its higher content, along with the foliar spraying at critical stages and the favorable effects of vermicompost on enhancing the availability of native nutrients and facilitating chelation.

Rani *et al*. (2022) evaluated the macronutrient requirements and the effects of agronomic biofortification of Fe and Zn on the yield and nutritional quality of finger millet. In terms of the method of $ZnSO_4$ application, foliar application was more effective than soil application at both 100% and 150% RDF. The treatment with the highest Zn content was 150% RDF with $ZnSO_4$ 0.5% foliar spray, which was 35.9 per cent higher than 100% RDF. For Fe content in the grain, the treatment with highest Fe content was 150% RDF with foliar spray of $ZnSO_4$ @ 0.5% and $FeSO_4$ @ 0.2%, 48.5 per cent higher than 100% RDF.

Micronutrients are typically added in conjunction with the appropriate macronutrient fertilization (NPK). It is widely recognized that the plant's nitrogen (N) status significantly affects the levels of Zn and Fe in vegetative tissues. Experimental indication suggests that the combined application of micronutrients along with macronutrients has a positive effect on increasing grain yield compared to using NPK alone(Cakmak, 2010). Prasad *et al*. (2015) studied to investigate how nitrogen (N) and zinc (Zn) fertilizers affect Zn biofortification in pearl millet. The Zn content in grain varied significantly based on the N and Zn rates, reaching its maximum with 60 kg N ha^{-1} and 10 kg Zn ha^{-1}. There was a significant interaction between N and Zn, with the highest Zn content (26.1 mg kg^{-1}) observed with 20 kg N with 5 kg Zn ha^{-1}.

Progress in fertilizer types that boosts agronomic biofortification

Inorganic fertilizers are essential for meeting crop nutrient needs, whether applied to soil, foliage, or using other methods. Agronomic biofortification can be achieved with micronutrient formulations like $ZnSO_4$, $FeSO_4$, $CuSO_4$ and $MnSO_4$. Combining Zn and Fe increases grain levels of Zn, Fe, crude fiberand protein, while Fe alone boosts grain Fe content (Niyigaba *et al.,* 2019). However, misuse of these fertilizers can harm the environment by causing water pollution, algal bloomsand biodiversity loss (Zhang *et al.,* 2019). Additionally, they are costly for bulk soil application and labor-intensive, which can be burdensome for small-scale farmers. Proper scheduling of fertilizer applications for optimal biofortification and economic benefit is also challenging and crop-specific. Recent advancements in fertilizer technology, including improved nutrient forms, contentand particle sizes, aim to enhance biofortification efficiency (Rodrigo *et al.,* 2014).

Biofertilizers are microbial inoculants containing microorganisms that enhance the growth and productivity of host plants (Bhardwaj *et al.,* 2014). Microbial intervention is recommended as a strategy to combat Zn deficiency (Dotaniya *et al.,* 2016). Nano fertilizers contain active ingredients in the 1-100 nm size range, either dispersed or encapsulated in the host material (Bhardwaj *et al.,* 2022). They offer a sophisticated, targetedand efficient nutrient delivery system with a high surface area-to-volume ratio, making them effective for slow-release and improved nutrient supply. They not only enhance plant growth but also increase the nutrient content in the plant's consumable parts (Li *et al.,* 2016).

Table 4: Biofortified millet varieties (Yadava *et al.,* 2017).

Variety/Hybrid	Grain yield (q/ha)	Maturity (days)	Fe (ppm)	Zn (ppm)
Pearl millet				
Dhanshakti	22.9	76	81	43
HHB 299	32.7	81	73	41
AHB 1200 Fe	32	78	73	
Phule Mahasakthi	29.3	88	87	41
RHB 233	31.6	80	83	46
RHB 234	31.7	81	84	46
Finger millet				
CFMV1 (Indravathi)	31.1	110-115	58	44
VR929 (Vegavathi)	36.1	118	131.8	
Little Millet				
CLMV 1 (Jaicar Sama-1)	15.8	98-102	59	35

Agronomic Biofortification in Comparison to Other Techniques

The effectiveness, feasibility and sustainability of agronomic biofortification compared to methods like genetic biofortification, food fortification, supplementation and dietary diversification are not well-established. Economic assessments often neglect agronomic biofortification in their evaluations. Generally, genetic biofortification proves more cost-effective than food fortification, supplementation, or dietary diversification due to its single breeding investment. While genetic biofortification is seen as a long-term solution, agronomic biofortification is viewed as a temporary method for improving micronutrient availability (Garcia *et al.,* 2014). Cakmak *et al.* (2010) argue that breeding is the only method that significantly enhances the nutritional value of staple crops in low-income areas where fertilizers may be unaffordable. The CGIAR biofortification program considers dietary diversity the most sustainable approach, though it may be financially inaccessible for the most vulnerable populations. Biofortified millet varieties are given in Table 4.

CONCLUSION

Agronomic biofortification in millets holds great promise as most effective and sustainable approach for addressing the prevalent micronutrient deficiencies and enhancing the nutritional value of these essential crops. Investing the development of agronomic biofortification methods also reinforces the effectiveness of genetic and conventional biofortification by expanding the availability of micronutrient forms. To ensure micronutrient enrichment in plants and fight against hidden hunger, this approach should be a primary focus for of future efforts. Analyzing various agronomic biofortification approaches used in various studies, can conclude that the most effective approach for crops is the combination of soil and foliar application, followed by foliar spraying, soil application, seed priming and soilless cultivation is the least preferable method. Millets are a group of small grains with the potential to significantly contribute to combating malnutrition, thereby potentially making India free from micronutrient malnutrition.

Conflict of interest

All authors declare that they have no conflicts of interest.

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