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Abhishek Jakhar
PG Student, School of
Agriculture, Uttaranchal
University, Dehradun,
Uttarakhand, India

Atin Kumar
Assistant Professor, School of
Agriculture, Uttaranchal
University, Dehradun,
Uttarakhand, India

Sharad Pandey
Professor, School of
Agriculture, Uttaranchal
University, Dehradun,
Uttarakhand, India

Rajendra Prasad
Professor, School of
Agriculture, Uttaranchal
University, Dehradun,
Uttarakhand, India

Nilotpal Das
PG Student, School of
Agriculture, Uttaranchal
University, Dehradun,
Uttarakhand, India

Corresponding Author:
Atin Kumar
Assistant Professor, School of
Agriculture, Uttaranchal
University, Dehradun,
Uttarakhand, India

Effects of foliar applications of micronutrients on growth and yield of chickpea

Abhishek Jakhar, Atin Kumar, Sharad Pandey, Rajendra Prasad and Nilotpal Das

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Abstract

Chickpea is one of the important pulse crops grown generally with rain-fed and marginal conditions, where micronutrient deficiency is a major constraint on plant growth, nodulation, and grain productivity. The foliar application of micronutrients has proven to be a viable option to enhance the efficiency of nutrient use and to combat nutrient limitation due to soils, especially in critical growth phases. Among micronutrients, zinc (Zn), boron (B), iron (Fe), molybdenum (Mo), manganese (Mn), and copper (Cu) are important for the physiology and biochemical reactions such as chlorophyll synthesis, enzyme activation, the process of photosynthesis, pollen viability, nitrogen fixation, and protein synthesis in chickpea. Rapid absorption of nutrients and immediate correction of deficiencies into the leaves, leading to improved vegetative growth, flowering, pod formation, seed filling, and productivity of the crop. Foliar nutrient application has been found to enhance the growth, dry matter production, nodulation, pods per plant, weight of seeds, and grain yield of chickpea in several studies. Moreover, micronutrient application enhances the quality of seeds, protein content, uptake, and stress tolerance in adverse environmental conditions. Zinc and boron are especially effective in enhancing the reproductive development and yield attributes among the various micronutrients. The use of foliar micronutrient application along with balanced nutrient management practices helps to ensure sustainable chickpea production and better economic returns. Thus, foliar nutrition can be viewed as a viable, economical, and environmentally friendly strategy to boost the growth, yield, and nutrient contents of chickpea under varying agro-climatic conditions.

Keywords: Chickpea, foliar application, micronutrients, growth and yield, nutrient management

Introduction

Chickpea (*Cicer arietinum* L.) is an important pulse crop globally and ranks third among the world's most widely grown legumes, with high nutritional value as a source of dietary protein, particularly in parts of the world where vegetarian diets are the norm, and animal protein is scarce. Its cultivation is spread across more than 17 million hectares in the global scenario, and more than 60% of the world's production is supported in India, where it holds a significant economic and nutritional role in subsistence and commercial farming (Kumar *et al.*, 2025; Rawat *et al.*, 2023). In addition to being a source of high-quality protein, fiber, vitamins, and minerals like iron and zinc, chickpea also plays a significant role in sustainable agriculture by fixing atmospheric nitrogen and enhancing soil fertility, which minimizes the need for synthetic fertilizers (Kumar *et al.*, 2025; Rawat *et al.*, 2023)^[23].

Although chickpeas are a valuable crop, they are often limited by micronutrient deficiencies in soils that are widespread in many important chickpea-producing areas, including intensive cropping systems and low inherent soil fertility (Meena *et al.*, 2025; Rawat *et al.*, 2023). These gaps not only reduce the yield and quality of crops but also impact the nutrition of humans who depend on chickpea as a staple food, potentially leading to hidden hunger due to the lack of micronutrients (Jha *et al.*, 2024; Meena *et al.*, 2025). Specific agronomic practices are needed to address these challenges. Of these, foliar application of micronutrients has proven to be an effective way to get quick correction of micronutrient deficiencies during the critical growth phase. Foliar applications of these provide effective nutrient assimilation as they avoid soil-related issues like fixation and/or poor nutrient mobility, resulting in better plant growth parameters, grain yield, protein content, and grain quality (Rawat *et al.*, 2023; Meena *et al.*, 2025)^[19, 24, 32].

Recently, it has been shown that foliar application with Zinc, Iron, Boron and other micro elements improved the growth indices (plant height, dry matter accumulation), yield attributes (number of pods per plant, seed weight), and nutritional quality (protein content) of chickpea in comparison with the untreated and the application of these elements in soil singly (Rawat *et al.*, 2023; Meena *et al.*, 2025). Our results show the dual purpose of foliar feeding, that is, enhancing productivity in agriculture and simultaneously enriching the grains of chickpea with target micronutrients, thereby biofortifying the grain. Current research, therefore, includes the optimization of foliar nutrient formulation and application time for yield and nutritional results. This review aims to bring together recent advances in the role of micronutrients in chickpea cultivation, including through foliar nutrition, and to consider their impact on chickpea performance, grain quality, and reducing micronutrient malnutrition ^[24, 32].

2. Overview of Chickpea Production

The chickpea (*Cicer arietinum* L.) is an annual, self-pollinated, herbaceous legume that is cultivated in temperate, semi-arid, and arid regions, producing podded seeds in the form of “desi” and “kabuli” types (Begum *et al.*, 2023; Yeasmen & Orsat, 2024). Chickpeas are a type of dry edible seed that have a protective seed coat and a well-developed taproot, making them suitable for low-input systems and adding to soil fertility through biological nitrogen fixation, which is significant in sustainable crop rotations (Begum *et al.*, 2023; Yeasmen & Orsat, 2024).

Currently, about 17 million tons of chickpeas are produced worldwide annually and have started to rise significantly in the 21st century (Begum *et al.*, 2023). India is the leading producer with about 70-71% share of world production of chickpeas, followed by Pakistan, Turkey, Australia, Ethiopia, Myanmar, and Iran (Begum *et al.*, 2023). Recent estimates suggest that Asia is the largest producer of chickpeas, accounting for more than 80% of the global production, with India producing approximately 11 - 12 million tonnes of chickpeas each year (Yeasmen & Orsat, 2024). Although at this scale, average yields are still a long way below optimal yields of up to 6 t ha⁻¹ (Arriagada *et al.*, 2022; Yeasmen & Orsat, 2024), there is still a significant yield gap ^[8, 44].

Abiotic stresses like drought, heat, cold, and salinity are major constraints on chickpea productivity, especially under the arid and semi-arid conditions and in low-quality soils where the crop is grown (Arriagada *et al.*, 2022). Large yield losses are attributed to drought and warming effects globally, and drought alone can result in yield losses of up to ~50% while warming effects in combination with lower rainfall further reduce yield (Arriagada *et al.*, 2022). Productivity is also constrained by biotic stresses such as Ascochyta blight and Fusarium wilt as well as insect pests (Singh *et al.*, 2022; Muche & Yemata, 2022). Poor soil fertility and the deficiency of some macro- and micro-nutrients in many chickpea cultivation areas also limit growth, nodulation, and yield, making the need to improve soil fertility and nutrient management essential to address the yield gap (Ali & Bhattacharjee, 2023; Rao *et al.*, 2023) ^[4, 26, 30, 39].

3. Concept of Foliar Nutrition: Foliar nutrition is the ability to provide the essential plant nutrients directly to the

leaves in the form of water-based sprays, in addition to soil application. The principle of this approach is that mineral nutrients can be taken up by leaves through the cuticle and, to a lesser degree, stomata, so nutrient deficiencies can be corrected quickly and mineral nutrients during critical growth periods and under stress conditions can be supplemented (Ishfaq *et al.*, 2022). The absorption mechanism of foliar application is more complex and includes the following steps: After being deposited on the leaf surface, the nutrients must pass through the leaf cuticle, which in turn permeates depending on the thickness, wax content, and presence or absence of pores; if the stomatal opening is open, the nutrient can enter the leaf. Once absorbed, the nutrients are transferred to other tissues via phloem and used in the metabolic processes of the plants, like photosynthesis and protein synthesis (Ishfaq *et al.*, 2022; Dass *et al.*, 2022) ^[11].

Foliar feeding has been proven to have some benefits. Foliar application can help to rapidly address nutrient deficiencies because it does not face soil-related constraints such as nutrient fixation, poor mobility, or soil pH, which can inhibit root uptake. It is especially useful under environmental stresses such as drought and heat stress that may decrease root activity and soil nutrient availability (Ishfaq *et al.*, 2022). According to the result of the meta-analyses, foliar fertilization can boost the production by 15-19% and enhance the quality traits by 9-29% under three different environmental stresses (Ishfaq *et al.*, 2022). Foliar nutrition also enables accurate timing and dosage of all the nutrition stage-specific requirements of a crop, thereby optimizing the use of the resources and minimizing fertilizer losses.

But foliar feeding has its drawbacks. It is dependent on the leaf surface properties, including cuticle thickness, waxiness, environmental factors (humidity, temperature, and wind), formulation properties (solubility, molecular size), and the physiological condition of the plant (Ishfaq *et al.*, 2022; Dass *et al.*, 2022). For instance, thicker cuticles or high wax content may hinder the uptake of the nutrients; likewise, if the rainfall takes place shortly after spraying, applied nutrients may be washed off before they can be absorbed. The efficiency of foliar nutrient uptake varies from one nutrient to another, based on their molecular size and the plant's nutrient requirement (Dass *et al.*, 2022). Also, repeated applications might be required for long-lasting results, but could result in a higher expense and risk of leaf burn if the concentration is high ^[17].

The efficiency of foliar uptake is also affected by endogenous factors (e.g., leaf age and leaf anatomy), exogenous factors (e.g., nutrient concentration in the solution and pH of the solution), and environmental factors (e.g., timing of the foliar application relative to environmental conditions) (Dass *et al.*, 2022). Good absorption generally takes place under warm and humid conditions, and in low winds, and some adjuvants, like wetting agents and/or stickers, can help cover the leaves and stick the product. Solubility and compatibility with other agrochemicals will also influence uptake rates, depending on the type of fertilizer used, such as chelated or inorganic salts ^[11].

To summarize, foliar nutrition is a valuable management tool for crop success in today's agriculture and a quick way of meeting nutrient needs in a stressful situation. It depends on the interpretation of the mechanism of absorption by

leaves, formulation selection, careful timing of application, and plant-specific and environmental factors. Foliar feeding is not a substitute for soil fertilization in most soil settings; however, it is an effective tool to bridge the gap and could be used in a more sustainable agricultural production system if added to an integrated nutrient management plan (Ishfaq *et al.*, 2022; Dass *et al.*, 2022)^[11, 17].

4. Role of Essential Micronutrients in Chickpea

Molybdenum (Mo) is an important microelement for chickpea and other grain legumes as it is a cofactor of two important enzymes, nitrogenase and nitrate reductase, which play a central role in biological N fixation in the root nodules and in nitrate reduction in plant tissues, respectively

(Banerjee & Nath, 2021). In this role, Mo directly participates in nitrogen metabolism and protein synthesis, contributing to the robust vegetative growth and seed's protein content (Banerjee & Nath, 2021). In addition to its physiological functions, Mo is also involved in several biochemical processes such as photosynthesis, carbohydrate and sulphur metabolism, which affect energy production, assimilate transport, and plant vigor (Banerjee & Nath, 2021). Mo deficiency affects nodule formation and Rhizobium activity, nitrogen fixation, and yield and quality of nutrition of chickpea and other legumes, particularly in acidic soils where available Mo is very low, with the effects being more pronounced in Mo-deficient soils (Banerjee & Nath, 2021) (Figure 1)^[7].

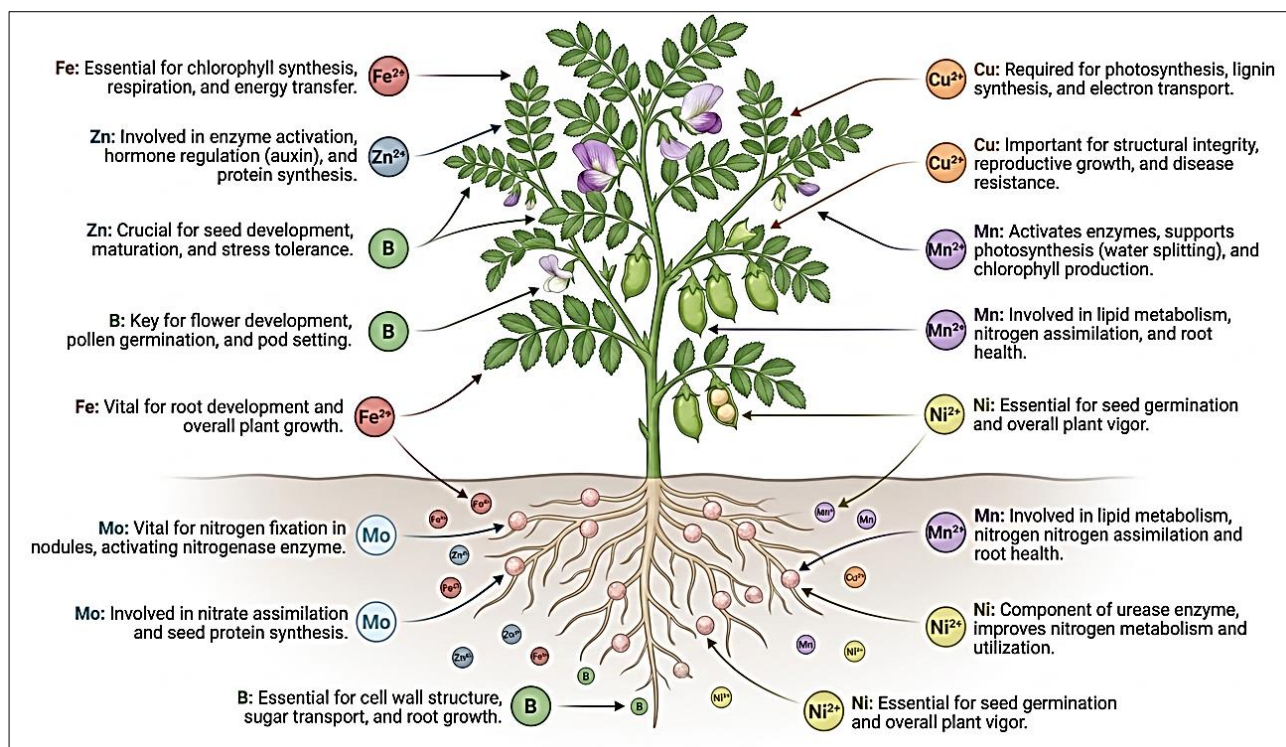


Fig 1: Micronutrients enhance chickpea growth and yield.

Figure 1. The diagram shows the role of various micronutrients on the growth, physiological, nodulation, flowering, and yield of the chickpea plant. The micronutrients Fe, Zn, B, Mo, Cu, Mn, and Ni are involved in various beneficial plant functions such as chlorophyll synthesis, nitrogen fixation, enzyme activation, pollen formation, root development, and seed production, to enhance plant health and productivity.

It is well established that zinc (Zn), boron (B), iron (Fe), and manganese (Mn) play a key role in enzyme activation, redox reactions, hormone regulation, and structural stabilization in higher plants. These factors control photosynthesis, chlorophyll biosynthesis, cell wall biosynthesis, hormonal signaling, and coping with stress; these activities are largely shared by most of the dicotyledonous crops, including legumes (Arinaitwe *et al.*, 2026). Zn is important for many Zn metalloenzymes and transcription factors, growth, auxin synthesis, membrane stability, and defence; deficiency causes reduced growth and leaf expansion, as well as reduced reproductive development (Arinaitwe *et al.*, 2026). B is crucial for cell wall integrity, membrane function, and reproductive processes such as pollen tube growth and fruit set; inadequate B leads to poor flowering and pod

development (Arinaitwe *et al.*, 2026). Fe is essential for electron transport in photosystems and respiration, biosynthesis of chlorophyll, and several oxidoreductases, and deficiency leads to a reduction in photosynthesis and chlorosis (Arinaitwe *et al.*, 2026). Mn is involved in the water splitting complex of photosystem II and enzymes of the tricarboxylic acid cycle and antioxidant metabolism; Mn deficiency leads to disruption of photosynthesis and oxidative stress (Arinaitwe *et al.*, 2026).

These micronutrients, along with Cu, Ni, and Cl, which are also important cofactors for photosynthesis (Phe), urease activity, and osmotic and ionic balance, are essential for good grain quality and high yield of chickpea, and their balanced supply is important for proper nitrogen metabolism, reproductive success, stress tolerance, and good grain quality^[3].

5. Foliar Application of Zinc in Chickpea

The foliar application of zinc (Zn) in chickpea is to provide a quick correction of Zn deficiency and improve growth, plant physiology, and grain quality by providing direct foliar nutrition rather than soil nutrition. The use of foliar application of Zn (particularly in chelated and soluble

forms) is more effective than soil application for enhancing Zn levels in reproductive organs with comparatively small applications of fertilizer (Jabri *et al.*, 2022; Silva *et al.*, 2025). In chickpea, foliar Zn has raised more grain N concentration than soil Zn, thus, enhancing N metabolism and seedling vigor of the next generation could also be beneficial (Jabri *et al.*, 2022). At a broader scale, Zn plays a role in sustaining better early establishment under stress by improving water uptake, membrane stability, and nutrient homeostasis that further contribute to seed germination and early seedling growth (Shao *et al.*, 2023; Ganguly *et al.*, 2022) ^[18, 38].

Zn is important for the synthesis of chlorophyll and photosynthesis, for the protection of the photo apparatus from oxidative stress, for improving the content of chlorophyll, stomatal function, and carbon fixation (Shao *et al.*, 2023; Ganguly *et al.*, 2022; Hassan *et al.*, 2022). In the cases of abiotic stresses (salinity, heavy metals), Zn application has been shown to enhance chlorophyll, activities of photosystems, biomass, and thus sustaining photosynthesis and growth processes (Shao *et al.*, 2023; Ganguly *et al.*, 2022; Hassan *et al.*, 2022). Nitrogen fixation in legumes is tightly coupled with their nodulation and

nitrogen metabolism and Zn nutrition is closely associated with an improvement in their water status, root development, plant growth, and overall plant growth and development which consequently leads to better nodulation and nitrogen fixation in chickpea, though some species-specific data are available (Shao *et al.*, 2023; Jabri *et al.*, 2022; Hassan *et al.*, 2022) ^[15, 36].

Some crops showed an efficiency of foliar Zn compared to soil application for increasing grain Zn concentration; in several crops, a single foliar application of Zinc Sulphate at reproductive stages resulted in a 25-40% increase in zinc grain concentration without any impact on yield, making it an efficient agronomic biofortification tool (Silva *et al.*, 2025; Hassan *et al.*, 2022). In chickpea, foliar Zn (particularly Zn EDTA) was more effective than soil Zn in improving grain N concentration, suggesting enhancement of the grain fraction nutritional quality and Zn use efficiency as compared to soil Zn (Jabri *et al.*, 2022). These applications allow foliar Zn to be targeted during the reproductive life stage, leading to a higher Zn pool in the foliage and improved translocation to grain, thus increasing agronomic Zn use efficiency and dietary value of chickpea (Table 1) ^[16, 18, 38].

Table 1: Effects of Foliar/Applied Zinc on Key Traits

Trait / Outcome	Typical Zn-related effects (legumes/crops, incl. chickpea where available)	Citations
Seed germination & seedlings	Higher germination, better seedling growth and vigor, improved water and nutrient status, and more N in chickpea grain for the next generation	(Shao <i>et al.</i> , 2023; Jabri <i>et al.</i> , 2022) ^[18, 36]
Chlorophyll & photosynthesis	Increased chlorophyll content, protected photosystems, improved CO ₂ fixation, and biomass under stress	(Shao <i>et al.</i> , 2023; Ganguly <i>et al.</i> , 2022; Hassan <i>et al.</i> , 2022) ^[15, 16]
Nodulation & N fixation (indirect)	Improved plant nutrition and N status; higher grain N in chickpea with foliar Zn suggests enhanced N assimilation	(Jabri <i>et al.</i> , 2022; Shao <i>et al.</i> , 2023) ^[18, 36]
Yield & grain Zn / quality	Foliar Zn at reproductive stages raises grain Zn 25-40% without yield loss; greater grain N/protein and Zn use efficiency	(Silva <i>et al.</i> , 2025; Jabri <i>et al.</i> , 2022; Hassan <i>et al.</i> , 2022) ^[16, 18, 38]

6. Foliar Application of Boron in Chickpea

Boron (B) application in chickpea is done foliarly to target critical growth and developmental processes in which B has been known to be essential in higher plants. B belongs to the large group of structural elements present in cell walls and membranes, where it is a component of borate-pectin complexes that contribute to the integrity and elasticity of rapidly growing tissues like floral organs, pollen tubes, and developing pods and seeds (Álvarez-Herrera *et al.*, 2025). B is also closely related to sugar transport and stability of membranes and enzymes of carbohydrate metabolism (Álvarez-Herrera *et al.*, 2025).

The B status is very sensitive in all flowering processes, such as proper development of pistils and anthers, pollen production, pollen germination, and elongation of pollen tube, favouring an adequate B status. B deficiency results in poor pollen viability, abnormal or ruptured pollen tubes, floral abortion, and decreased fruit or seed-set; such symptoms have been observed in most of the fruit crops, and are mechanistically correlated with cell wall weakness, irregular Ca-pectate formation, and reduced carbohydrate provision to reproductive organs (Álvarez-Herrera *et al.*, 2025). The use of foliar B is beneficial because B is relatively immobile in many species, so sprays near or just before flowering result in higher levels of B in buds and flowers, which boost pollen tube growth, initial fruit set, and retention (Álvarez-Herrera *et al.*, 2025). Based on the analogy, chickpea flowers and pods are also potential B-

demanding sinks, and are expected to respond to well-timed foliar B during pre-flowering to early pod set.

Boron also stimulates the flow of assimilates to developing pods and seeds. All these changes, such as decreased sugar transport in phloem, acidity and pH, increased respiration, and ascorbic acid degradation, are indicators of carbohydrate partitioning disturbances caused by B deficiency (Álvarez-Herrera *et al.*, 2025). However, with respect to the fruits, suitable B results in better filling and high soluble solids levels (Álvarez-Herrera *et al.*, 2025; Bons & Sharma, 2023). This means greater translocation of photosynthates to grain legume seeds, improved pod filling, and better seed size and uniformity in grain legumes.

In reproductive crops, yield and quality responses to foliar B are well described. In pomegranate (and other fruit species), foliar B (alone or with other nutrients) has been consistently found to promote fruit set, lower fruit drop, increase fruit size and mass, and improve fruit quality (firmness, soluble solids, vitamin C, color) by strengthening the cell walls and supporting sugar movement (Bons & Sharma, 2023; Álvarez-Herrera *et al.*, 2025). Increased pod number and seed set per flower, improved seed development, and increased yield and nutritional quality are among the physiological functions associated with a positive effect of foliar B on chickpea and are the factors expected to contribute to positive impacts on chickpea under B optimization (Table 2) ^[2, 9].

Table 2: Key roles of foliar boron relevant to chickpea

Function/Outcome	Boron-related process (general evidence)	Citations
Flowering & pollen viability	Cell wall/membrane integrity in anthers, stigma, and pollen tubes; improved pollen germination and tube growth; reduced floral abortion	(Álvarez-Herrera <i>et al.</i> , 2025) ^[2]
Pod setting & seed development	Better B supply to reproductive sinks, higher fruit/seed set and retention, fewer deformed or aborted fruits/seeds	(Bons & Sharma, 2023; Álvarez-Herrera <i>et al.</i> , 2025) ^[2, 9]
Carbohydrate transport	Enhanced sugar movement in phloem, improved TSS, regulated respiration, and organic acid balance	(Bons & Sharma, 2023; Álvarez-Herrera <i>et al.</i> , 2025) ^[2, 9]
Yield & quality	Increased set, size, firmness, soluble solids, and vitamin C; reduced cracking and physiological disorders, better post-harvest quality	(Bons & Sharma, 2023; Álvarez-Herrera <i>et al.</i> , 2025) ^[2, 9]

7. Foliar Application of Iron and Other Micronutrients

In chickpea, foliar application of iron and other micronutrients is intended to correct the hidden deficiencies that are common in Indian and other legume-growing soils. Thus, large-scale soil and foliar micronutrient deficits of Fe, Cu, and Mn, and other micronutrients are common in soils, and their deficiency reduces the productivity and quality of nutritional components in the grain products, so soil or foliar micronutrient fertilization is recommended to increase the yield and nutrient density of grain products (Shukla *et al.*, 2021) ^[37].

Iron (Fe) plays a key role in chlorophyll biosynthesis, photosynthesis, and respiration, as well as in the function of numerous enzymes and electron transport components (Bagale, 2021; Ning *et al.*, 2023). In legumes, deficiency of Fe causes interveinal chlorosis and reduced photosynthesis, while in cereals, chlorosis occurs between the veins and is characterized by an obvious loss of chlorophyll from the interveinal chlorosis spots. (Bagale, 2021). Foliar application of Fe, preferably chelates, has been commonly applied to remedy iron deficiency chlorosis, as soil limitations (high pH, bicarbonates) do not apply to foliar application, and it directly restores chlorophyll and photosynthetic performance (Bagale, 2021; Ning *et al.*, 2023) ^[6, 27].

Manganese (Mn) is involved in the photosynthetic water splitting complex and as an activator of many enzymes in central metabolism and antioxidant defense; deficiency decreases growth and yield in many crops (Obeng *et al.*, 2024; 2021). Copper (Cu) is another essential metal in addition to Fe, with its presence in the foliar tissue being required for proper flower and seed development (Shukla *et al.*, 2021), but no chickpea-specific foliar Cu data were provided in these papers ^[28, 37].

Grain legumes have a special requirement for molybdenum (Mo). It is also a cofactor of nitrogenase and nitrate reductase, which directly catalyzes the biological nitrogen fixation in rhizobial nodules and nitrate reduction in plant tissues (Banerjee & Nath, 2021; Bagale, 2021). High and sufficient Mo application enhances nodule formation, N assimilation, protein synthesis, and yield in pulses, particularly in acidic and Mo-deficient soils (Banerjee & Nath, 2021) ^[6, 7].

Combined or multi-micronutrient (e.g., Fe+Zn) application to soil, as well as foliar application, can boost micronutrient levels in grains or pods and sometimes yield, but this varies depending on soil type and environment (Szerement *et al.*, 2021; Thapa *et al.*, 2021; Shukla *et al.*, 2021) ^[37]. Combining basal soil fertilization with foliar application of Fe and other essential metals (Mn, Cu, Mo) to chickpea grown on micronutrient deficient soils is therefore a promising option for supporting the formation of chlorophyll, activation of enzymes, nitrogen metabolism,

reproductive growth and overall productivity, in addition to providing better micronutrient density in the grain and reducing “hidden hunger” (Banerjee & Nath, 2021; Szerement *et al.*, 2021; Shukla *et al.*, 2021) ^[7, 37, 42, 43].

8. Interaction of Micronutrients with Macronutrients

The relationship between micronutrients and macronutrients plays an important role in plant growth, nutrient use efficiency, and sustainable nutrient management. Nitrogen (N), phosphorus (P), and sulfur (S) interact with zinc (Zn) and iron (Fe) closely, and their combinations have both synergistic and antagonistic effects on the uptake, transport, and signalling of the latter ions in plants (Fan *et al.*, 2021; Saquee *et al.*, 2023) (Figure 2) ^[14, 34].

Figure 2. The diagram shows the flow of nutrients through the xylem and phloem in the plant system, as well as the interaction between the macro and micronutrients. It emphasizes the synergistic effects of nutrients like iron, zinc, boron, and molybdenum on their contribution to the transport of phosphorus, nitrogen metabolism, potassium mobility, and overall nutrient assimilation for better plant growth and development.

N supply can be used to enhance the uptake and internal redistribution of Zn and Fe to improve delivery to seeds and the nutritional quality of the grain (Saquee *et al.*, 2023). At the signalling level, two types of interactions between N and P and between N and Zn have been documented; changes in N status lead to changes in the expression and activity of P and Zn transport systems, thereby coordinating N and P and Zn acquisition under multiple stresses (Fan *et al.*, 2021). However, high levels of P (inorganic phosphate, Pi) can inhibit both Zn and Fe uptake, while Zn deficiency can increase Pi uptake, showing high P-Zn (and P-Fe) antagonism at both the root and transcriptional level (Fan *et al.*, 2021; Saquee *et al.*, 2023). Unbalanced N or P fertilization can result in hidden micronutrient deficiencies because of these relationships, even if soil micronutrient levels are adequate ^[34].

INM considers the integration of macro and micronutrient inputs while introducing specific amounts of micronutrients either in the form of NPK fertilizers or through organic/biological inputs. The synergistic effects of micronutrients when applied with macronutrients significantly improved plant growth, grain yield and quality traits as demonstrated in various reviews; understanding the interactions, particularly the antagonism between P-Zn and Fe-Zn uptake, and the enhancement of micronutrient uptake when applied with macronutrients (e.g., N-Zn/Fe uptake) is critical to designing an effective fertilizer program (Saquee *et al.*, 2023; Fan *et al.*, 2021) ^[34]. Application of an integrative multiple nutrients approach is considered essential for nutrient homeostasis and sustainable farming in multiple nutrient stresses (Fan *et al.*, 2021) (Table 3) ^[14].

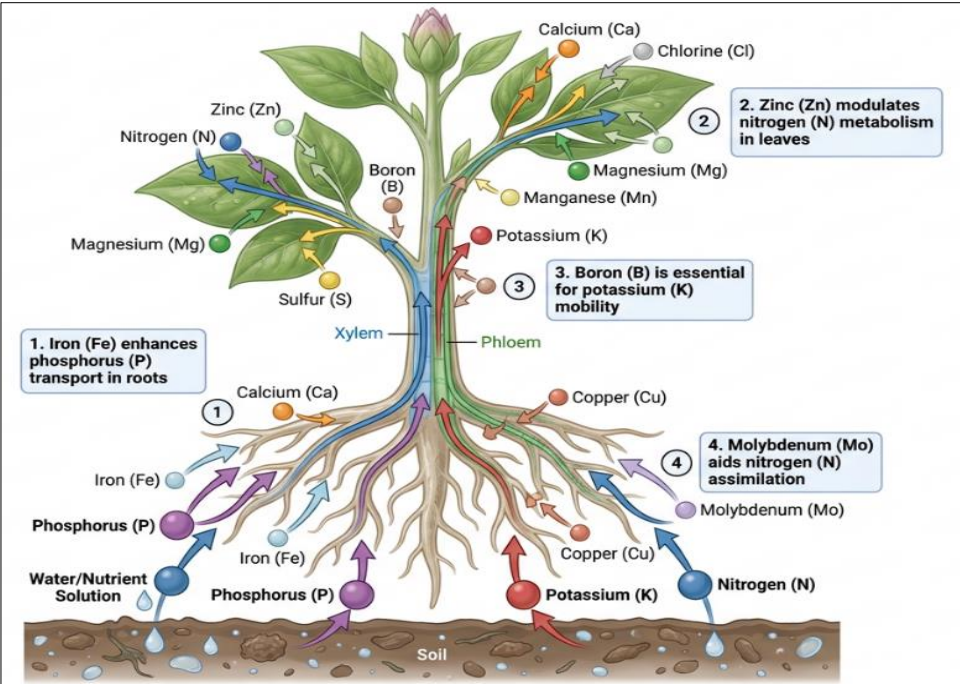


Fig 2: Nutrient interactions improve plant development.

Table 3: Key macro-micro interactions relevant to management

Interaction type	Example relationships and implications	Citations
Synergistic	N with Zn and Fe enhances uptake, root-shoot transfer, and seed loading; N-P and N-Zn signaling cross-talk improves coordinated acquisition	(Fan <i>et al.</i> , 2021; Saquee <i>et al.</i> , 2023) ^[14, 34]
Antagonistic	High P reduces Zn and Fe uptake; Zn deficiency increases Pi uptake; some S fertilization can depress Mo; imbalances can induce hidden deficiencies	(Saquee <i>et al.</i> , 2023; Fan <i>et al.</i> , 2021) ^[14, 34]

9. Effect of Foliar Micronutrients on Physiological and Biochemical Parameters

The effects that micronutrients have on physiological and biochemical plant traits associated with photosynthesis and stress tolerance can be strong when delivered through a foliar application. Most work is not on chickpea, but on various crops; underlying processes (photosynthetic machinery, enzymes, antioxidants, proteins) are common to higher plants, so the mechanisms are relevant. Micronutrient foliar sprays can improve the efficiency of photosynthesis by shielding and/or optimizing the photosynthetic apparatus. Under salinity and drought, foliar application of selenium (Se) enhanced the net photosynthetic rate, stomatal conductance, transpiration, and photochemical efficiency (Fv/Fm), and maintained the chloroplast structure of wheat, tea, rice, and other species (Khan *et al.*, 2023). Under the drought conditions, the copper oxide (CuO) and zinc oxide (ZnO) based nanoparticles applied foliarly increased the PSII efficiency, electron transport, gas exchange, and light absorption, which resulted in better photosynthetic performance (Szerement *et al.*, 2021)^[42]. Repeatedly reported positive effects on the chlorophyll content. In wheat, foliar Se enhanced the total chlorophyll and other photosynthetic pigments, which correlated with growth under arsenic, salinity, or drought stress (Khan *et al.*, 2023). A similar increase in chlorophyll a and b was obtained in pulses and oilseeds with Nano-chelated micronutrients (Zn, Fe, Mn, Cu), which resulted in better light capture and photosynthesis (Banerjee & Nath, 2021). The microminerals are also important in regulating enzyme function and protein biosynthesis. Under stress, application

of Se increased the activities of antioxidant enzymes such as SOD, CAT, APX, and GR and increased nitrogen and protein content in the leaves of basil and other crops (Khan *et al.*, 2023). Nano chelates in pulses and oilseeds improved the levels of soluble proteins and increased the levels of some of the major antioxidant enzymes (SOD, CAT, POD), which means increased metabolic capacity and defense (Banerjee & Nath, 2021). Also, it is observed that a sufficient supply of micronutrients such as Mo is favorable for the activity of enzymes related to nitrogen metabolism, like NR and nitrogenase, which are essential for promoting the physiological growth and seed protein content of legumes (Rasheed *et al.*, 2022)^[31]. In terms of antioxidant activity and stress tolerance, foliar application of Se and Se-nanoparticles improved the enzymatic and non-enzymatic antioxidants, osmoprotectants (proline, soluble sugars), membrane stability, K⁺/Na⁺ balance, reduced ROS (O₂⁻, H₂O₂), lipid peroxidation, and enhanced yield under salinity and moisture stress (Khan *et al.*, 2023). The antioxidant enzyme activities and proline accumulation in chickpea, mung bean, and soybean under nano-chelated micronutrients significantly enhanced drought and salinity tolerance and their biomass and yield (Banerjee & Nath, 2021). At a broader scale, foliar micro- and nano nutrient application has been highlighted as effective technologies for maintaining photosynthesis, chlorophyll, enzyme activities, protein status and antioxidant defense under various abiotic stresses, further indicating the potential of such application, if judiciously used in chickpea crop systems (Khan *et al.*, 2023; Szerement *et al.*, 2021; Banerjee & Nath, 2021; Rasheed *et al.*, 2022)^[7, 20, 31, 42].

10. Influence on Growth Parameters

While micronutrients and related inputs (e.g., Mo fertilizers, foliar Fe, Zn) primarily affect chickpea growth parameters through their impact on nitrogen metabolism, photosynthesis, and general nutrient uptake, and not as direct 'growth hormones.' These internal changes, in turn, are mirrored in plant height, branching, root growth, biomass (dry matter), and leaf area index (LAI).

The role of molybdenum is central because it is the cofactor of two important enzymes for the symbiotic nitrogen fixation in legumes (nitrogenase) and for nitrate reduction in plant tissues (nitrate reductase) (Banerjee & Nath, 2021). An increase in better N metabolism leads to improved rates of protein synthesis, photosynthesis, and carbohydrate metabolism, resulting in improved vegetative growth. In the case of grain legumes such as chickpea, Mo fertilization has been consistently linked to "magnification of physiological growth", higher yield potential, and better nutritional quality (Banerjee & Nath, 2021). This generalized gain suggests increased plant height, shoot biomass, and branching because of the more vigorous canopy.

There is also an indirect improvement in root development due to the effect on N status and optimization of other nutrient availability by Mo, which leads to increased root growth and activity, thus promoting increased nutrient and water foraging (Banerjee & Nath, 2021). The deeper and more extended root system results in increased total dry matter production. Good practices that boost N assimilation, chlorophyll production, and carbohydrate production to growing leaves, like proper Mo or foliar micronutrient application, will improve LAI and keep it higher throughout the season^[7].

Across crops, micronutrient management (often in combination with macronutrients) increases plant growth and physiological traits, and is emphasized as crucial for realizing yield potential and quality (Kovács *et al.*, 2022). Improved N fixation, nutrient use efficiency, and photosynthetic capacity are likely to be mechanisms behind the positive response to well-balanced micronutrient supply in chickpea for plant height, branch number, root development, dry matter accumulation, and LAI^[22].

11. Influence on Yield Attributes and Yield

Foliar micronutrient applications affect multiple yield components, which contribute to grain and straw yields. While most detailed quantitative data are for cereals and oilseeds, and not for chickpea, all the yield components (pods or spikes, seed number, seed weight, biomass, harvest index) are impacted due to improved nutrient status, particularly through foliar sprays at critical growth stages (Saquee *et al.*, 2023; Ishfaq *et al.*, 2022; Thapa *et al.*, 2021). In terms of yield components such as number of pods/plant and seeds/plant, soybean yield reviews indicate that foliar micronutrients (typically Zn, Fe, Mn, Cu and B) applied together have a significant impact on the number of reproductive structures; e.g., increased number of pods/spike, grain/spike, and number of pods/plant as well as increased grain number (Saquee *et al.*, 2023; Thapa *et al.*, 2021). The increased response of reproductive sinks to corrected micronutrient deficiencies, such as in soybean, where foliar B and mixed micronutrients improved pod number per branch, grain number, and seed weight per plant (Thapa *et al.*, 2021), highlights the potential for foliar micronutrient rates to be fine-tuned based on specific crop needs.

Consistent improvements in 100 seed (or 1000 grain) weight are always reported. In wheat, spraying foliar mixtures of Cu, Fe, Mn, and Zn significantly improved 1000 grain weight, straw, and biological yield (Saquee *et al.*, 2023). For soybean, foliar B or Cu and mixed Fe-Zn-Mn sprays resulted in increased thousand seed weight and seed size, which indicated improved seed filling (Thapa *et al.*, 2021).

The component gains lead to an increase in biological yield, harvest index, and grain and straw yield. For foliar micronutrients, wheat straw yield, biological yield, and HI were increased alongside grain yield, which suggests that there was an increase in total yield and improved partitioning of biomass to grain (Saquee *et al.*, 2023). For soybeans, soil plus foliar micronutrient application (Zn, Fe, Mn, B, Mo, Cu) resulted in increases in biomass, grain yield by as much as 40% or more, and improved grain quality (protein, oil, mineral content); An application of micronutrients regulates enzymes and metabolic pathways associated with growth and assimilate allocation in soybean (Thapa *et al.*, 2021).

Overall, evidence presented that well-timed foliar micronutrient sprays could improve several yield components such as reproductive structure number, seed grain size, biomass production and harvest index leading to higher grain and straw yields across crops, with this to be expected when sprays are targeted according to crop phenology and site-specific micronutrient deficiency (Saquee *et al.*, 2023; Ishfaq *et al.*, 2022; Thapa *et al.*, 2021)^[17, 34, 43].

12. Effect on Nutrient Uptake and Quality of Chickpea

Biofortification strategies are aimed at improving nutrient uptake and grain quality of chickpea, while retaining grain yield, and can be categorized as agronomic-based or biological-based. In chickpea and other pulses, emphasis is laid on improving the mineral density of seed and straw, boosting protein levels, and improving the quality of seeds with regard to human nutrition. Soil, foliar, and nanofertilizer application of micronutrients (including Zn, Fe, and Se) can significantly boost the micronutrient levels in edible parts of various crops and can also lead to an increase in the protein and amino acid content and other micronutrients like phenolics, carotenoids, and essential oils (Szerement *et al.*, 2021). In Grain Legumes, molybdenum fertilization has been consistently associated with the improvement in nutritional value of seeds, such as higher protein content as seen in chickpea and other pulses, which directly supports N metabolism and protein synthesis (Banerjee & Nath, 2021).

The agronomic biofortification of grains and other parts of the plant for nutrient concentration in seed and straw involves enhancing the nutrient concentration in the crop, only if the dose is optimized to prevent biomass penalties (Szerement *et al.*, 2021). This enrichment is key for the biofortification potential as low soil micronutrient availability is one of the primary drivers of low grain mineral density and 'hidden hunger' (Szerement *et al.*, 2021). Mo optimization also has indirect benefits for other essential nutrients due to its effects on the phyto-availability of those nutrients, which are also reported to be high in chickpea seeds and residues (Banerjee & Nath, 2021). In terms of seed quality traits, micronutrient biofortification can increase the targeted mineral level as well as antioxidants and related bioactive compounds, thus enhancing the food nutritional value and health benefits from consuming food from biofortified crops (Szerement *et*

al., 2021). The overall improvement in N metabolism (Mo) and micronutrient status of the crop is beneficial for protein content and quality of pulses in general, and especially for chickpea, which is a protein- and mineral-rich staple (Banerjee & Nath, 2021) [7, 42].

13. Foliar Micronutrients under Abiotic Stress

Conditions: Abiotic stresses like drought, heat, and salinity are stressing crops and result in an increasing need to use foliar application of micronutrients. This results in reduced absorption of nutrients from soil and causes oxidative stress, osmotic stress, and metabolic disturbances in plant tissues; exogenous application of the micronutrients (e.g., Zn, Fe, Se) directly to the leaves alleviates some of the negative effects of the deficiency and boosts stress resistance.

Zinc is especially important under stress conditions of salinity. When plants are grown in saline environments, Zn application (including foliar routes) enhances seedling growth, water uptake, plant water relations, and nutrient homeostasis (Shao *et al.*, 2023). It prevents the damaging effects of oxidative stress that occurs due to salinity on the photosynthetic apparatus, regulates chlorophyll biosynthesis and stomatal activity, and improves carbon fixation. Zn also stimulates the build-up of osmolytes and hormones, which in turn enhance antioxidant enzyme activities and secondary metabolites and thereby decrease ion toxicity and oxidative damage, resulting in better salinity tolerance (Shao *et al.*, 2023). Growing plants agrobiofortified with Zn, Se, and Fe also increases ROS scavenger enzymes (SOD, APX, CAT, GPX, GR, etc.) and non-enzymatic antioxidants (glutathione, ascorbate, carotenoids, and proline), which help maintain redox and ionic balance and, in turn, reduce the impact of salt stress on plants (Damalas & Koutroubas, 2024) [36].

With the drought stress, micronutrient biofortification with Zn, Se, and Fe boosts plant growth and yield, as well as drought tolerance largely through increased antioxidant systems and the water relations of the plants (Damalas & Koutroubas, 2024). These result in a higher activity of ROS detoxification enzymes and higher levels of accumulation of osmoprotectants, which prevent damage to membranes and maintain photosynthesis and transpiration in water-deficient conditions (Damalas & Koutroubas, 2024) [10].

Regarding heat stress, there is less information on the direct effect of micronutrients on the leaves, but the same

antioxidant and protection mechanisms of Zn, Se and Fe on salt and drought stress described above are also valid for high/low temperature stress; in this situation, increased levels of enzymatic and non-enzymatic antioxidants reduce ROS and cellular injury due to heat stress (Damalas & Koutroubas, 2024). In general, micronutrients play a crucial role in stress alleviation mechanisms that involve strengthening antioxidant activity, osmotic adjustment, photosynthetic stability, and nutrient homeostasis under drought, salinity, and temperature stress conditions (Shao *et al.*, 2023; Damalas & Koutroubas, 2024) [10, 36].

14. Methods and Timing of Foliar Application

The effectiveness and safety of foliar micronutrient sprays are highly dependent on the methods and timing of application. The solution concentration, the proper growth stage of the plants, the number of times the solution is applied, the coverage of the droplets, and the mixtures of foliar fertilizers with pesticides or biofertilizers are important. The recommended concentrations are such that they do not scorch the leaves, but are adequate to correct the deficiencies. Too high foliar rates can scorch leaves, particularly at high temperatures; adequate rates quickly overcome leaf deficiencies and enhance stress tolerance (reviews). Moderate concentration of ZnSO₄ (typically 0.3-0.4% w/v) solutions are generally used to achieve successful biofortification, often supplemented by a surfactant such as Tween 20, which does not harm the grain, and not at levels high enough to produce chlorosis in leaves (Shahrajabian *et al.*, 2022). The recommended amount for Se and other micronutrients is highlighted as low level in the g ha⁻¹ range to prevent toxicity, but still provide enrichment of the grain (Ssemugenze *et al.*, 2025). The timing with respect to the growth stage is key. The stages of high nutrient demands and high leaf area are best suited for foliar sprays. In cereals (and for many legumes), repeated application of sprays from flag leaf to grain filling, or close to flowering and early pod/grain formation, has repeatedly been shown to be the most effective time for application to maximize effects on grain nutrient content and yield (Ssemugenze *et al.*, 2025; Shahrajabian *et al.*, 2022). Basal ZnSO₄ at sowing and foliar Zn application at flowering and pod formation resulted in the highest level of grain enrichment for chickpea (Ssemugenze *et al.*, 2025) (Figure 3) [34, 41].

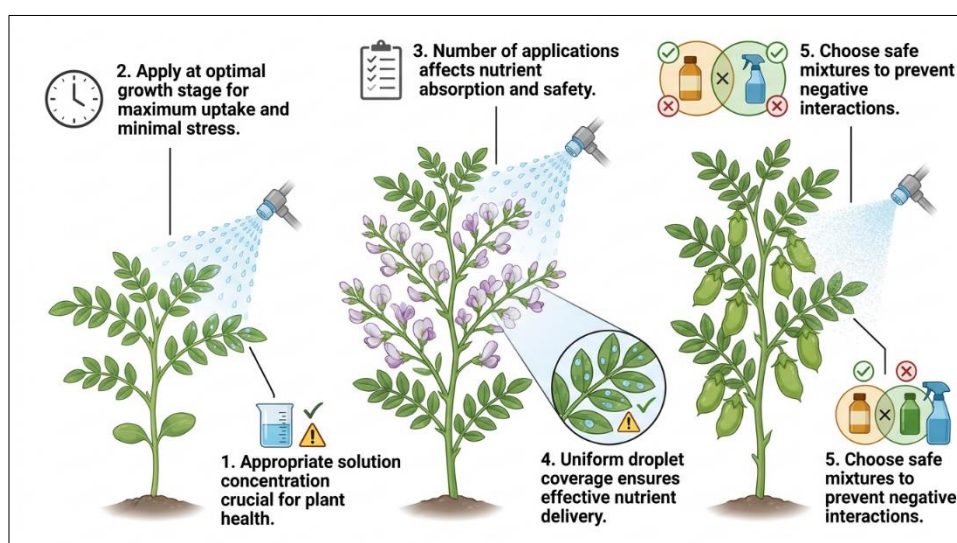


Fig 3: Foliar nutrition improves plant productivity.

Figure 3. The diagram demonstrates the major factors affecting the success of foliar nutrient solutions in plants: solution concentration, nutrient solution growth stage, frequency of application, uniform spray cover, and safe nutrient solution mixtures. These practices guarantee optimum nutrient retention, reduce plant stress, and improve growth, flowering, and yield.

The application is often made once, twice, or 3 times a season or even every ~10 days during the critical reproductive period, depending on the season, as opposed to frequent small sprays throughout the season (Ssemugenze *et al.*, 2025). Fine droplets, uniform leaf coverage, and calm and mild weather (moderate temperature, low wind, no imminent rain) are highlighted as key factors to minimize drift and wash-off (Ssemugenze *et al.*, 2025). Labor and passes over the field can be reduced by tank-mixing some pest and disease control sprays with foliar fertilizers;

compatibility must be tested with each product, and foliar fertilizers are recommended to be used as a supplement to soil fertilization under salt and/or other stresses (Ssemugenze *et al.*, 2025). In terms of compatibility with biofertilizers, several studies on the compatibility of pesticides and microbial inoculants indicate that the survival and activity of the rhizobia and other beneficial bacteria are drastically affected by the contact time, active ingredient, and dose of the product, depending on the fungicide and insecticide (Sánchez-Palacios *et al.*, 2023). The results suggest that, in the case of microbial inoculants-based systems, foliar micronutrients should be used with great care, since the use of pesticides in combination with biofertilization can reduce the effectiveness of the latter, as it has been observed in this work with sulfur- and zinc-based products (Sánchez-Palacios *et al.*, 2023) (Table 4)^[33, 41].

Table 4. Practical foliar strategies (concentration, timing, frequency)

Aspect	Typical practice/recommendation drawn from recent reviews	Citations
Concentration	Moderate micronutrient solutions (e.g., $\text{ZnSO}_4 \approx 0.3\text{-}0.4\%$ w/v) with adjuvant; avoid high doses that scorch leaves	(Shahrajabian <i>et al.</i> , 2022; Ssemugenze <i>et al.</i> , 2025) ^[35, 41]
Growth stages	Flag leaf to grain filling; flowering + pod/grain formation; pre-filling for Se; similar reproductive stages in legumes	(Ssemugenze <i>et al.</i> , 2025; Shahrajabian <i>et al.</i> , 2022) ^[35, 41]
Frequency	1-4 sprays, often 1-2 key applications or 10-day intervals across reproductive stage; always supplemental to soil fertilization	(Ssemugenze <i>et al.</i> , 2025) ^[35, 41]

15. Economic Analysis of Foliar Micronutrient Application:

The use of foliar micronutrients is not only recommended for agronomic purposes, but also for economic interest, particularly in situations of soil deficiencies and/or stress, as well as in situations of restricted fertilizer budgets. Economic evaluation is concerned with cost-benefit ratio, net returns, efficiency of use of resources, and acceptability to the farmers. In all crops, foliar application of micronutrients (alone or with macronutrients) is often reported as an economically sound approach small doses, targeted times of application, and quick uptake can have a significant impact on yield and grain quality without necessarily having a corresponding increase in inputs. A literature review on wheat micronutrient fertilization has stated that foliar application is the “very profitable” method, and is recommended as the most promising method in comparison to soil-only application methods in terms of economic, agronomic, and ecological efficiency (Saquee *et al.*, 2023). The same review emphasizes that foliar micronutrients, particularly with macronutrients, boost yield components, grain yield, and quality, leading to better economic returns per unit of nutrient applied (Saquee *et al.*, 2023)^[34].

Foliar fertilization is recommended from a wider picture of resource use, to ensure high nutrient use efficiency, and minimise losses of fertiliser, directly enhancing the cost-benefit ratio. Amongst maize, foliar fertilization at critical growth stages is reported to be the most effective way of maximizing the utilization of nutrients, increasing yield and quality, and importantly increasing the nutrient use efficiency, decreasing the cost of fertilizers, and consequently increasing the profit margin for the producers as they have minimized nutrient runoff, reduced environmental pollution, and improved soil health (Ssemugenze *et al.*, 2025). This suggests increased returns per unit of nutrient added as well as per cash invested, and is

an important measure of the efficiency in the use of resources and the economic viability^[41].

In terms of farmers' adaptability, both reviews emphasize that foliar sprays are primarily supplementary, not replacement, methods. Favored conditions for adoption are: (1) When sprayable products can be mixed in the tank with other sprays, reducing the amount of labor and machinery needed; (2) When deficiencies and/or yield responses are easily observable and consistent; and (3) When information is available on correct timing and concentration. However, practical and cost constraints like multiple applications, suitability of weather conditions during application, and risk of leaf burn are cited as potential factors that may slow the uptake by farmers (Ding *et al.*, 2023; Ssemugenze *et al.*, 2025)^[13].

In general, evidence indicates that, when applied to the nutrient deficient situation and critical growth stages, foliar micronutrient application has generally good potential for good cost-benefit ratios and better economic returns through yield and quality improvements, better resource use efficiency, and good potential for farmer adaptability, provided there is extension support and appropriate formulations of the micronutrients (Saquee *et al.*, 2023; Ssemugenze *et al.*, 2025)^[34, 41].

16. Environmental and Sustainability Aspects

A sustainable increase in the production of pulses requires the reduction of the losses of these materials, an increase in the efficiency of their use, and a reduction in pollution. Interest in micronutrients and nanofertilizers, and related inputs has recently shifted towards the targeted delivery, controlled release, and combination with the biological approach to achieve these objectives. Sound micronutrient nutrition can reduce losses of soil nutrients and enhance micronutrient use efficiency. For instance, providing small amounts of Ni ($0.05\text{-}5 \text{ kg ha}^{-1}$) increases the efficiency of urea N conversion in crops, which helps reduce the losses of

N as N_2O , NH_3 , and NO_3 from the over-applied urea (Rabinovich *et al.* 2024). When Ni sorption is high in the soils, foliar rates may be more practical, and can be programmed into the existing foliar nutrient programs, with very low soil loading and within the regulatory limits (Rabinovich *et al.*, 2024). In general, nano and bionanofertilizers have controlled release and targeted delivery properties, which minimize the risks of eutrophication and acidification of the soil and reduce runoff, leaching, and volatilization losses compared with conventional soluble fertilizers, thus reducing the risk of eutrophication and soil acidification (Demeke *et al.*, 2025). The efficiency improvements will help with sustainable pulse production because nutrient inputs will be more efficient in delivering nutrients to the crop, resulting in cost and environmental benefits. Nanofertilizers can be used to improve the root system, the ability to tolerate stress, and soil microbial activity, which will help to maintain soil fertility and long-term productivity instead of exhausting soil resources (Demeke *et al.*, 2025). Abiotic stresses associated with calcium disorders can be reduced by Ni management, thus limiting excessive irrigation and Ca application, resulting in water and input losses (Rabinovich *et al.*, 2024). In terms of environmental security, the use of Ni micronutrients and nanofertilizers is both conceived as low-dose technologies that should be regulated and risk assessed, and as technologies. In the name of environmental security, both Ni micronutrient use and nanofertilizers are conceived as low-dose technologies that should be regulated and carefully analyzed for risks and hazards and as technologies. When recommended agronomic rates are followed, the consumer exposure to this Ni from urease activation will be well below rates associated with toxicity, and Ni is highly mobile in plants, so it is not expected to be accumulated in edible tissues at these rates, and the consumer risk is considered low (Rabinovich *et al.* 2024). With the nanofertilizers, the reviews stress the need for regulatory mechanisms, ecotoxicity tests, and monitoring of soil and water systems to guarantee a safe, climate-smart nutrition management, while questioning the potential to reduce pollution due to their uncertainties in soil and water fate and ecotoxicity (Demeke *et al.*, 2025)^[12, 29, 12].

17. Challenges and Limitations

While foliar micronutrient applications may significantly boost yield and quality, there are various challenges that limit the application's reliability, safety, and utility across environments. One of the drawbacks is that there are variations in field response. The response of plants to foliar fertilization is influenced by several interacting factors, such as leaf age, species, nutrient status, growth stage, foliar solution formulation or preparation, droplet deposition, and environmental conditions (moisture, temperature, rainfall, wind) (Sotiropoulos *et al.*, 2023). This complex interaction often makes it hard to predict when spray will provide a positive yield response, and large variations in field results are often reported with the same product (Ishfaq *et al.*, 2022; Sotiropoulos *et al.*, 2023). Factors which influence the responses include the type of particle and its dose, size, surface properties, plant species, exposure time, and the duration of exposure; these factors make it difficult to make meaningful comparisons across studies and make it difficult to draw broad conclusions about nanofertilizers and nanoparticle-based foliar inputs (Avellan *et al.*, 2021).

The high level of toxicity is a concern due to the very small difference between beneficial and harmful doses, particularly for nanoparticles. The main issues that the current reviews highlight for foliar nanofertilizer are the unaddressed “toxicity and environmental residue” concerns, the need for optimal dose rate for each crop, and the potential phytotoxicity caused by excessive doses (Avellan *et al.*, 2021). A need for fine-tuning of doses to achieve adequate accumulation in the edible parts without compromising growth and quality and to preclude potential toxicity to plants, animals, and humans has been repeatedly emphasised for wider agronomic biofortification with Se, Zn, and Fe (Ishfaq *et al.*, 2022). A clear lack of location and crop-specific recommendations is also evident. There are no resources or materials available to conduct basic soil characterization (pH, organic matter, salinity, moisture) in many biofortification and foliar studies, which poses difficulty in extrapolating results and creating site-specific guidelines (Ishfaq *et al.*, 2022). More multi-location, multi-genotype field experiments under realistic combinations of stress factors are recommended to establish best practices for the various environments and species (Ishfaq *et al.*, 2022)^[5, 17].

Last but not least, climatic impacts on foliar absorption are important limitations. The penetration and efficacy of sprays are highly dependent on temperature, humidity, and rainfall; post-spray rain can leach out products; suboptimal temperatures or low humidity can result in reduced penetration and/or damage of the leaves (Sotiropoulos *et al.*, 2023). For foliar nanoparticles, the lack of agreement regarding the exact uptake and translocation pattern is large, as exposure protocols (dose, spraying vs. other methods, time after application) and growth conditions for the plants are unknown (Avellan *et al.*, 2021). All these restrictions emphasize the importance of precise dosage, increased reporting of environmental conditions, and larger site-specific research before giving out general recommendations without any risk^[5, 40].

18. Future Research Perspectives

Research on foliar micronutrient application and biofortification of chickpeas is progressing toward “smarter materials” and “more precise delivery”, as well as towards closer integration with “climate-resilient, nutrition-focused” farming. The development of nanofertilizers, nano-hybrid formulation, and non-transgenic biofortification has several clear directions. Optimization of the size of the nanoparticles, their surface chemistry, and coatings that lead to good leaf binding, good foliar uptake, and controlled movement to edible tissues while keeping doses and losses to a minimum, is a priority for nano-micronutrient formulations and precision foliar nutrition. In order for the deployment of nanoformulations for Fe, Zn, and Se biofortification through foliar spraying and seed priming to be widely adopted, standardized synthesis and characterization protocols, large-scale field validation, and cost-effective, reproducible production are necessary (Minello *et al.*, 2025; Szerement *et al.*, 2021). The assessment of accumulation in edible tissues, the long-term environmental fate, and potential toxicity of products as part of regulatory frameworks is also emphasized^[25].

In the context of climate-smart agriculture, future research is expected to integrate into both the production of resilient crops (including intercropping and soil-plant-microbiome

management), and the use of nano or advanced foliar micronutrients to boost stress defense, while also optimizing both biofortification and stress defense for low-input systems (Szerement *et al.*, 2021). More research is needed in different types of field climates and soils, as well as under different water stress, salinity, and heat conditions, which are underrepresented. Next steps involve, at the molecular level, linking foliar/nano-micronutrient delivery to plant transporters, chelators, regulatory genes that control loading of Zn, Fe, and Se into seeds, and achieving increased nutrient density and bioavailability using omics and gene editing tools while retaining yield (Szerement *et al.*, 2021). For chickpea and other pulses, research gaps involve multi-nutrient foliar strategies, an agronomic vs genetic approach for biofortification, and real diet (human) bioavailability of enriched grains (Szerement *et al.*, 2021). Overall, the combination of engineered nano-foliar inputs, molecular breeding, and sustainable agronomy is considered to be the primary avenue towards scalable, climate-resilient chickpea biofortification (Minello *et al.*, 2025; Szerement *et al.*, 2021) [25, 42].

19. Conclusion

In the context of enhancing growth, yield, and quality of chickpea under varying agro-climatic conditions, foliar application of micronutrients has been proven to be effective and efficient. The results of different studies have shown that the application of micronutrients like zinc, boron, iron, molybdenum, manganese, and copper alone has increased the physiological and metabolic activities, resulting in improved plant growth, nodulation, flowering, pod-set, seed filling, and grain production. Foliar feeding also enhances the nutrient assimilation efficiency, chlorophyll production, protein synthesis, and tolerance to stress conditions, especially in nutrient-deficient soils and rain-fed environments. In the micronutrients, zinc and boron were observed to have significant effects on reproductive growth and enhancement of yield in chickpea. The significance of foliar micronutrient application is that the nutrients can be quickly absorbed, lost to a lesser extent, are inexpensive to implement, and correct deficiencies at key growth stages. It also helps to maintain balance in the nutrition and utilization of crops and reduces environmental risks of soil fertilization while ensuring sustainable agricultural production by enhancing the use efficiency of nutrients. To achieve high productivity, quality seeds, and better economic returns for sustainable chickpea production, the proper selection of micronutrients and their appropriate application in the leaves at adequate concentrations and growth stages, along with management of balanced fertilization, crop management, and soil nutrient management, should be considered.

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