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Enhancing barley yield through micronutrient application: A review

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Abstract

Barley (*Hordeum vulgare* L.) is a widely cereal crop worldwide that often suffers from Zinc (Zn) and Iron (Fe) deficiency in calcareous and intensively managed soils. Deficiencies restrict plant growth, yield and affect grain quality. Soil-based micronutrient application is inefficient due to fixation and leaching; foliar application is more efficient. This review explores the physiological and biochemical functions of Zn and Fe in barley, effects on growth characteristics, yield components and economic feasibility of foliar application. Studies have shown foliar Zn and Fe increase plant height, tillers, leaf area index, chlorophyll, grain filling, thousand grain weight and harvest index. Co-application is more effective than individual application, improving photosynthesis, enzymatic processes and nutrient transport. Financially, foliar micronutrient use has promising benefit-to-cost ratios as yields and quality enhance with low cost. Moreover, these micronutrients' biofortification potential meets human nutritional needs. But there are still unknowns regarding long-term impacts, varietal responses, nano-formulation effectiveness and stress tolerance. Research to integrate precision farming with new fertilizer technologies will further improve foliar micronutrient management for sustainable and high yielding barley production.

Keywords: Micronutrients, nutrient management, soil fertility, biofortification, sustainable agriculture

Introduction

Barley (*Hordeum vulgare* L.) is a staple cereal crop cultivated globally for food, feed and malting, especially in semi-arid and temperate zones. Despite its tolerance of poor growing conditions, barley growth is often limited by low levels of micronutrients, particularly zinc (Zn) and iron (Fe), found in intensively cropped and calcareous soils (Kihara *et al.*, 2024) [20]. These nutrient deficiencies are caused by the elevated soil pH, poor organic matter, and high nutrient fixation, which limits plants access to nutrients (Broadley *et al.*, 2022) [5]. These limitations not only jeopardise crop yield but also the nutritional status of grain, leading to human micronutrient deficiency. Traditional soil application of micronutrients has poor efficiency caused by fixation, leaching and low mobility in the soil and plant system (Abbas *et al.*, 2025) [1]. However, foliar application has been proven as a successful alternative to bypass such constraints by applying the nutrients directly to the leaves and enabling swift uptake and utilization of these nutrients during critical growth periods (Ullah *et al.*, 2025) [42]. Foliar feeding is especially beneficial in rectifying micronutrient deficiencies during the reproductive period when nutrient requirements increase but cannot be met via root absorption. Recent advances have shown that foliar supplementation of Zn and Fe markedly increases growth, harvest parameters, and crop nutrient use efficiency in cereals (including barley) (Tiware *et al.*, 2023) [40]. Additionally, foliar spraying of Zn and Fe has been found to have a complementry effect in enhancing plant functions, including photosynthesis, enzyme kinetics and translocation (Kihara *et al.*, 2024) [20].

Review of Literature

Physiological and Biochemical Functions of Zinc and Iron

Zinc and iron are micronutrients that are responsible for key physiological and biochemical processes, which affect plant growth, development and yield. Zinc has a broad spectrum of enzymatic functions, and is a structural and catalytic component of more than 300 enzymes participating in the protein formation, carbohydrates and nucleic acids (Alloway, 2021) [3].

It also forms a key constituent of tryptophan synthesis, precursor of auxin, and mediates cell growth and development. Zinc deficiency leads to dwarfism, smaller leaves and lesser biomass. Besides controlling plant growth, zinc stabilises cell membranes and protects the plants from the damage caused by stress and boosts antioxidant enzymes such as superoxide dismutase (Broadley *et al.*, 2022) ^[5]. It also enhances nitrogen metabolism and protein synthesis, contributing to crop productivity. Moreover, iron is important for redox reactions and enzyme function in nitrogen use and respiration (Broadley *et al.*, 2012). Its role in ATP production and energy transport is vital for crop metabolic activity and growth (Broadley *et al.*, 2022) ^[5]. Zinc and iron exhibit combined response, as they are involved in different pathways. Ample availability of these micronutrients improves nutrient absorption, enzyme co-regulations and tolerance to stress (Kihara *et al.*, 2024) ^[20]. Research shows that joint supplementation of Zn and Fe has a better effect on chlorophyll concentration, photosynthetic rate and biomass production than supplementing either one of these two nutrients (Tiwari *et al.*, 2023) ^[40].

Impact of Foliar Zinc and Iron on Barley's Growth Attributes

Growth parameters such as plant height, tiller number, leaf area index (LAI), and dry matter production are key indicators of crop response to micronutrient application. Zinc (Zn) and iron (Fe) have been extensively reported to positively affect these growth parameters in barley and other cereal crops, especially under conditions of micronutrient deficiency when applied through foliar means. Zinc is a key element for plant growth and development due to its role in auxin production and enzyme function. Foliar Zn application increases the availability of Zn, which is essential for cell growth and division, driving an increase in plant height and leaf area. For example, Singh *et al.* (2022) ^[37] observed marked increases in growth parameters such as plant height and tiller number of cereals after foliar Zn treatment, due to enhanced photosynthetic capacity and hormonal activity. Likewise, Kumar *et al.* (2021) ^[23] reported enhanced leaf area index and biomass production with the addition of Zn, suggesting enhanced vegetative growth.

Iron is also critical for growth, as it affects chlorophyll biosynthesis and photosynthesis. Fe foliar sprays have been reported to boost chlorophyll content and delay leaf senescence, leading to an increased leaf area index and biomass yield. Gupta *et al.* (2021) ^[12] reported a foliar Fe spray increased chlorophyll content and dry matter yield in cereal crops. Similarly, Hussain *et al.* (2020) ^[15] also showed higher dry matter production and plant vigor as a result of improved growth and metabolism.

Apart from promoting growth under well-watered conditions, foliar applications of Zn and Fe also enhance resistance to environmental stresses including drought and heat. Micronutrients help maintain membrane integrity and decrease oxidation stress by increasing the activity of antioxidant enzymes. Rehman *et al.* (2021) ^[32] found that Zn enhanced water use efficiency and decreased oxidative stress in cereals, enhancing growth under water stress. Likewise, Khan *et al.* (2022) ^[19] pointed out the importance of iron in sustaining the photosynthetic process and increasing plant tolerance against stresses.

In addition, foliar application of micronutrients improves nutrient absorption and translocation process. Enhanced nutrient translocation results in efficient transport of assimilates and eventually increased dry matter production and plant growth. Meena *et al.* (2021) ^[25] found substantial increases in biomass

and growth rate of cereals when Zn and Fe were applied as foliar spray, highlighting the role of micronutrients in crop production. Foliar applications require careful consideration of timing, concentration and environmental factors. Timely application at growth stages like tillering and early reproductive phases have been found to enhance nutrient efficiencies. Sharma *et al.* (2023) ^[36] found that the timely foliar application of micronutrients improved growth parameters over late foliar spraying, indicating the need for appropriate timing during micronutrient application. In summary, the present evidence is clear that foliar applications of Zn and Fe have a profound effect on the growth attributes of barley by improving physiological activities, including photosynthesis, enzymes, and nutrient uptake and utilization. Foliar spray with a combination of these micronutrients is more effective in enhancing vegetative growth and crop performance under both favorable and unfavourable circumstances. Yield and its related attributes are the ultimate outcome of crop production and are highly affected by the status of micronutrients such as zinc (Zn) and iron (Fe). Foliar micronutrients supply using zinc and iron have been reported to increase yield attributes, including spike characteristics including grain number, kernel mass, and overall yield in barley and comparable cereal species. Zinc plays important effects on reproductive development such as pollen development, fertilisation and grain setting. Sufficient Zn supply promotes enzyme activation and carbohydrate metabolism necessary for grain development. Yadav *et al.* (2022) ^[46] observed an increase in the spike length and grains per spike in cereals due to foliar Zn application which was explained by increased assimilate production and transport. Likewise, Reddy *et al.* (2022) ^[31] found a significant boost in grain yield with Zn foliar spray attributed to enhanced reproductive and nutrient use efficiency.

Iron plays a vital role in yield improvement by improving photosynthesis and carbohydrate production, which help in grain filling. Fe foliar application enhances chlorophyll content and sustains photosynthetic activities during the grain filling period. Verma *et al.* (2022) ^[43] documented that Fe foliar spray significantly enhanced the 1000-kernel weight and output in cereals. Similarly, Iqbal *et al.* (2021) ^[16] found increased grain filling and yield as a result of increased metabolic processes and energy metabolism. A combined application of Zn and Fe is shown to have a synergic effect on yield and yield components. The reason for this is that Zn is involved in the activation of enzymes while Fe is essential for energy metabolism. Raza *et al.* (2022) ^[30] found that the highest grain yield and yield attributes were achieved when Zn and Fe were co-applied through foliar sprays in comparison to their sole application. Likewise, Shah *et al.* (2020) ^[34], reported a substantial increase in spike length, grains per spike, and grain weight under combined micronutrient treatments, suggesting the significance of optimum nutrient supply. Foliar application also optimizes source-sink relationships in the plant leading to better assimilation of photosynthetic in the grains. Supply of nutrients during reproductive stages, i.e., flowering and grain filling, is also improved, contributing to better yield potential. Khan *et al.* (2021) ^[18] highlighted that foliar micronutrient treatments at flowering and grain-filling stages result in improved grain yield through better assimilate distribution.

Weather and timing are the key factors influencing the success of foliar micronutrient-effectiveness. Early reproductive and grain filling applications have been shown to increase yield Ahmad *et al.* (2022) ^[2] reported a higher grain yield with early foliar application compared to late application, highlighting the need for optimum timing. Foliar Zn and Fe application not only

enhances yield but also grain quality, such as protein concentration and micronutrient density, thus making a significant contribution to human nutrition Sing and Meena (2021) ^[25] observed improvements in grain quality and nutritional value by the application of Zn and Fe, highlighting their use in biofortification. In conclusion, foliar spraying of Zn and Fe remarkably increases yield and yield attributes of barley through improvement in physiological activities like photosynthesis, uptake and translocation of nutrients and assimilates. The co-application of these micronutrients is especially beneficial in enhancing yield potential and grain quality.

The yield components test weight (1000-grain weight) and harvest index are key measures of crop yield and efficiency, and reflect the efficiency of assimilate allocation between vegetative and reproductive structures. Spraying of zinc (Zn) and iron (Fe) has been found to have profound effects on these traits through enhancing physiological processes related to grain filling and biomass partitioning. Test weight is largely influenced by grain filling, which is related to assimilate availability and carbohydrate metabolism efficiency. Zinc is an essential element for carbohydrate metabolism and starch synthesis. Higher Zn availability from foliar application leads to better grain development through improved enzyme activities and assimilate translocation to the grain Patel *et al.* (2021) ^[27] found an increase in test weight of cereals due to foliar Zn application, which they linked to improved carbohydrate metabolism and grain filling. Likewise, Chaudhary *et al.* (2022) ^[7] found that Zn application increased grain weight owing to enhanced photosynthesis and transport processes.

Iron is involved in grain development through increased photosynthetic and energy transport efficiency, promoting starch biosynthesis during the grain-filling period. Exogenous foliar Fe application has been demonstrated to preserve chlorophyll levels and the duration of photosynthesis, leading to increased assimilate supply to grains Mishra *et al.* (2020) ^[26] found that Fe enriched plants greatly improved test weight by increasing photosynthetic efficiency and metabolic efficiency. Similarly, Banerjee *et al.* (2023) ^[4] found increases in grain weight and density because of enhanced energy use efficiency and assimilate translocation. Harvest index, which relates economic yield (the yield harvested) to biological yield (total dry matter produced), is a measure of crops' ability to convert biomass to grain yield. Spray application of Zn and Fe increases harvest index by improving the source-sink ratio and efficient assimilate allocation Das *et al.* (2021) ^[8] reported a substantial boost in harvest index when applied with foliar micronutrients, suggesting better partitioning of dry matter towards yield. Likewise, Jat *et al.* (2022) ^[17] found increased harvest index resulting from increased nutrient use efficiency and biomass allocation.

Integration of Zn and Fe has shown positive interactions with yield components. The optimum supply of micronutrients allows better functioning of physiological processes like photosynthesis, respiration and mineral assimilation which in turn helps in better grain formation and increased harvest index Kulkarni *et al.* (2023) ^[21] showed that combined foliar applications produced the highest test weight and harvest index when compared to single applications, demonstrating the benefit of interactions between micronutrients. Other factors such as environmental conditions and timing of application also play a crucial role. Micronutrient applications at the grain filling stage has been reported to yield maximum increase in test weight and harvest index by maintaining sufficient micronutrients during

critical grain development stages Tripathi *et al.* (2021) ^[41] stressed that appropriate time of application increases the rate and duration of grain filling, thereby improving various yield components. Also, the foliar application of Zn and Fe improves physiological efficiency (nutrient efficiency) by increasing nutrient uptake and utilization. Enzyme activities and metabolic pathways are improved and more assimilates are converted into grain biomass, resulting in higher harvest index Sarkar *et al.* (2022) ^[33] found micronutrient application boosted physiological efficiency and yield components in cereals. Hence, foliar application of Zn and Fe significantly improves test weight and harvest index in barley due to improved grain filling, assimilate conversion, and metabolic efficiency. The application of the combination of these two micronutrients is most effective in altering yield components and increasing productivity.

Economic Viability of Foliar Zn and Fe Supplementation in Barley

Financial sustainability is a key consideration for agronomic practices, especially in micronutrient management regimen like foliar spraying of zinc (Zn) as well as iron (Fe). Although benefits for plant physiology along with yield have been reported, adoption of such management strategies at the farmers' level is mainly determined by profitability measures such as production expenses, total returns, net profit, as well as cost-benefit analysis. Foliar Zn and Fe application is considered an economic input because of low nutrient dose, low cost of application and high physiological efficiency. Foliar application of nutrients is efficient as it overcomes the nutrient losses resulting from fixation, leaching and immobilization, compared to soil application, and enhances input-use efficiency and gross return Rani *et al.* (2021) ^[29] documented that leaf-applied, micronutrients boosted net returns in cereals due to enhanced yield response and lower fertilizer loss.

The increased gross return can mostly be attributed to an increase in grain yield and grain quality. Zinc and iron application enhance marketable yield by enhancing grain filling, test weight, and biomass partitioning Singh *et al.* (2020) ^[38] found micronutrient-fertilised treatments increased gross returns in barley production systems, mainly due to its higher productivity.

Net returns depend on the increase in yield and the cost of nutrient fertilisations. Given the low amount of foliar Zn and Fe applied, the cost of these nutrients is much lower than that of macronutrients. Verma *et al.* (2021) ^[44] reported an increase in net returns in cereal crops due to foliar application of micronutrients leading to increased yield efficiency and enhancement in crop value. The benefit - cost ratio (B:C) is commonly used indicator of economic returns for agricultural practices. Research indicates foliar application of Zn and Fe increases B:C ratio as a result of yield improvement without escalating costs. Kumar *et al.* (2022) ^[22] found that joint foliar application of Zn and Fe treatments had the highest B:C ratio than the control and individual Zn or Fe application, so it was most efficient.

Integrated nutrient management with foliar micronutrients are also found to improve resource-use efficiencies and profitability. Recently, Sharma *et al.* (2023) ^[35] found that the combination of Zn and Fe foliar application with recommended amount of fertilizer has shown maximum economic return in cereal systems. This demonstrates the need for nutrient balance for profitability. The grain price is another important economic indicator. Micronutrient can enhance grain quality traits like protein and mineral levels, which benefit its market value in

quality and health markets Patel *et al.* (2022) ^[28] reported that biofortified grain contributed to increased market price due to improved nutritive value and added to profitability. Another key economic benefit of foliar micronutrient application is the reduction in risk. Zn and Fe spray increases resilience to environmental stresses (e.g. drought, heat) to improve sustainable production with negligible seasonal yield variation Gupta *et al.* (2023) ^[13] showed the importance of micronutrient management in decreasing yield variability, and hence increasing the farmer's economic benefits. In conclusion, foliar Zn and Fe application is economically proven in barley as the cost of using the micronutrients is small, yield response is large, the quality of grain is better and the benefit-cost ratio is increased. Simultaneous use of these two micronutrients is also more lucrative due to additive effects on productivity while the production cost remains almost unchanged.

Potential Research and Development

Although significant advances have been made in understanding the effects of using foliar-applied zinc (Zn) and iron (Fe) to improve barley production, some key research gaps exist constraining their maximum agronomic benefits and widespread application. Current research primarily addresses short- to medium-term yield increases, and little is known about long term impacts, biogeochemical transformations and ecosystem responses. A key research gap is the dearth of genotype response studies. Barley cultivars differ in nutrient efficiency, including nutrient uptake, transport and use efficiency. White and Broadley (2020) ^[45] highlighted the strong genotype dependence of micronutrient efficiency, but few studies have been undertaken to link foliar micronutrient response with genetic variations in barley. This limits the ability to implement site-specific nutrient management for the different barley varieties. There is a need for long-term and multi-locate field experiments. These experiments are mostly conducted under controlled conditions or in one growing season, without considering variations over multiple years. Environmental factors (soil, rainfall and temperature) vary and affect the efficiency of micronutrients, hence precise recommendations cannot be made without region-specific efficiency and yield data of micronutrients, according to Zhao *et al.* (2021) ^[47]. So, multiple location testing is required for the recommendation of site-specific foliar applications.

Additionally, the interaction between foliar application of Zn and Fe other macro- and micronutrients is poorly understood. These may have a positive, negative or neutral impact on nutrient uptake Hänsch and Mendel (2020) ^[14] indicated that micronutrient interactions are important for regulating plant metabolic processes, but the majority of field experiments only assess Zn and Fe uptake and use in single or combined application. Another area that is lacking in research is advanced fertilizers such as nano-formulations. Traditional foliar fertilizers have low leaf penetration efficiency and are quickly washed off leaves. New research shows that nano-formulations of zinc and iron have a major impact on increasing uptake and minimizing fertilizer loss Dimkpa and Bindraban (2021) ^[9] found that foliar uptake and nutrient use efficiency increase when using nano-micronutrients, but the use of nano-micronutrients in barley systems is still unexplored. Second, the potential of integrating with precision agriculture is not being harnessed. Remote sensing, drones for nutrient mapping and the use of artificial intelligence (AI) in decision support tools can help to determine foliar application timing and rate. But as per Mahajan *et al.* (2022) ^[24], precision in nutrient management for

micronutrient fertilization is still very limited in the cereal crop production systems. Climate-wise, there is a lack of studies on the functions of foliar Zn and Fe under stress (drought, salinity and heat). The physiological and molecular basis of stress tolerance is unclear; although some studies suggest enhanced stress tolerance Farooq *et al.* (2021) ^[10] stress that micronutrient-induced stress resistance is a highly interesting area but needs more in-depth research, especially for barley.

Conclusion

Zinc (Zn) and Iron (Fe) are important micronutrients that are effective when applied as foliar spray to increase barley production in micronutrient-deficient soils. These micronutrients are essential for photosynthesis, enzyme activation, chlorophyll formation and carbohydrate metabolism, which in turn enhance plant growth, grain filling and yield components. Their combined application is more effective than individual application and remarkably enhances thousand-grain weight, harvest index and grain yield. From a cost-benefit analysis perspective, foliar application of Zn and Fe has a positive benefit-cost ratio, along with enhanced grain quality and biofortification. But there are still gaps in knowledge regarding long-term field experiments, genetic variability, nano fertilizers and mechanisms of stress tolerance. Research on these areas will enhance the importance of the foliar micronutrient application for sustainable and productive barley farming.

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