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Foliar nutrition of rice: A comprehensive review

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Abstract
Foliar nutrition has emerged as an efficient supplementary strategy to enhance nutrient uptake, growth, and productivity in rice, particularly under conditions where soil-based fertilization is limited by fixation, losses, or poor nutrient availability. Rice, a staple for more than half of the global population, demands innovative nutrient management approaches to sustain yields and improve grain quality. Foliar application enables rapid absorption of nutrients through leaf surfaces and can correct deficiencies more efficiently than soil fertilization. Recent advances demonstrate significant improvements in growth, yield, and physiological responses through foliar application of conventional fertilizers, nano-formulations, and organic liquid manures. Foliar sprays have also proven effective for micronutrient biofortification, particularly zinc enrichment, and for mitigating environmental stresses when combined with growth regulators or silicon-based formulations. Despite clear advantages, foliar nutrition remains a supplemental practice, with effectiveness influenced by environmental conditions and concentration-dependent phytotoxicity. Continued research on advanced formulations, precision delivery technologies, and sustainable organic alternatives will strengthen the role of foliar nutrition in resilient and high-quality rice production systems.

Keywords: Foliar nutrition, rice (*Oryza sativa* L.), micronutrients, nano-fertilizers, biofortification, nutrient use efficiency

1. Introduction

Rice (*Oryza sativa* L.) is more than just a cereal crop; it is a fundamental part of life for over half of the world's population. It provides not only daily nourishment but also cultural, economic, and social stability across much of Asia, Africa, and Latin America. According to the United States Department of Agriculture, global rice production now exceeds 520 million metric tonnes annually (USDA, 2024) [47], illustrating the enormous scale at which this crop sustains human populations. Apart from its energy rich carbohydrate content, rice also supplies essential vitamins such as niacin and riboflavin, along with minerals including iron, calcium, and phosphorus, making it a vital nutritional component in many developing regions.

India stands as the world's second largest rice producer, contributing nearly one-fourth of global rice output. Major states such as Telangana, West Bengal, Punjab, and Uttar Pradesh collectively form the heart of national rice cultivation. Rice farming also supports millions of livelihoods, with by products like straw, bran, and husk feeding into livestock, energy, and agro-industrial sectors. Yet, behind this vast production system lie pressing challenges that complicate the future of rice based food systems.

One of the most serious issues facing modern rice cultivation is the progressive depletion of soil nutrients. Continuous monocropping, intensive high yielding varieties, and insufficient nutrient replenishment have led to widespread deficiencies of macronutrients and micronutrients. Indian soils, for instance, exhibit zinc deficiency in more than 50% of cultivated areas (Verma *et al.*, 2018) [48]. At the same time, the fertilizers used to restore soil fertility are becoming increasingly inefficient. Only 20-50% of applied nitrogen is typically taken up by the rice plant, while the rest is lost through volatilization, leaching, denitrification, or immobilization (Shaviv and Mikkelsen, 1993; Zhang *et al.*, 2010) [41, 52]. Phosphorus, although abundantly applied often becomes fixed in insoluble forms, rendering it unavailable to roots. Such nutrient losses not only limit crop yields but also contribute to environmental problems such as groundwater contamination, eutrophication, and greenhouse gas emissions (Xu *et al.*, 2021) [50].

Climate change further magnifies these issues. Unpredictable rainfall, prolonged dry spells, and heat stress disrupt nutrient mineralization and root uptake, making fertilizer timing increasingly unreliable. Flooded rice systems, which undergo frequent shifts in redox potential, create additional barriers for nutrient availability, especially for micronutrients like zinc and iron. Under these fluctuating conditions, relying solely on soil applied fertilizers often fails to meet the plant's rapidly changing nutrient demands during critical growth stages.

These challenges have intensified interest in foliar nutrition, an approach that involves supplying nutrients directly to leaves. Unlike soil application, foliar fertilization bypasses soil-related constraints and allows rapid nutrient uptake, often resulting in visible physiological improvement within days. Under optimal conditions, foliar-applied nutrients can achieve uptake efficiencies exceeding 80%, significantly improving the performance of high-yielding rice varieties, particularly during sensitive developmental stages such as tillering, panicle initiation, and grain filling (Kannan, 2010) [18]. Foliar feeding is also especially effective for correcting micronutrient deficiencies such as zinc and iron, which are often difficult to manage through soil application alone.

Recent advancements in foliar technology, including chelated nutrient solutions, nano-nutrient sprays, silicon based formulations, biostimulants, and drone-assisted precision spraying have expanded the scope and efficiency of foliar fertilization in rice. These innovations offer improved absorption, better mobility within plant tissues, enhanced stress tolerance, and opportunities for nutritional quality improvement through biofortification.

In the context of increasing food demand, soil degradation, rising fertilizer costs, and climate instability, sustainable nutrient management has become more critical than ever. Foliar nutrition presents a promising complementary strategy to traditional soil fertilization, offering pathways to enhance nutrient use efficiency, improve crop resilience, and support sustainable rice production systems. This review therefore synthesizes current knowledge on the mechanisms, applications, benefits, limitations, and emerging innovations in foliar fertilization, with a focus on its role in modern rice cultivation.

2. Foliar nutrition in rice

2.1 The need for foliar nutrition in modern rice systems

In rice based cropping systems, the efficiency of soil applied fertilizers has become increasingly constrained by both agronomic and environmental factors. Although fertilizers remain essential for sustaining high yields, intensive cultivation with high yielding varieties has accelerated nutrient depletion in soils, while the overuse and unbalanced application of chemical fertilizers has contributed to a significant decline in soil health. Nitrogen, the most widely applied nutrient in rice farming, typically exhibits a recovery efficiency of only 20-50%, with the remaining nutrients escaping through multiple pathways, including volatilization, leaching, denitrification, and soil fixation (Shaviv and Mikkelsen, 1993; Zhang *et al.*, 2010; Xu *et al.*, 2021) [41, 52, 50]. Similar inefficiencies occur with phosphorus, which becomes fixed in insoluble forms shortly after application, and with micronutrients like zinc, iron, manganese, and copper, which often remain unavailable due to soil pH constraints or redox reactions in flooded fields (Shaygany *et al.*, 2012) [42]. These losses not only reduce nutrient use efficiency but also increases the risks of water contamination, eutrophication, and greenhouse gas emissions, posing a challenge to the sustainability of rice ecosystems.

India's rice soils illustrate this challenge particularly well, as widespread deficiencies of sulphur, magnesium, calcium, and several micronutrients have increasingly been observed. Zinc deficiency affects more than half of Indian agricultural soils, while sulphur deficiency has become more common with the shift towards highly concentrated fertilizers that lack secondary nutrients. Under flooded conditions typical of lowland rice, sulphate may be reduced to sulphide, restricting its plant availability and inadvertently intensifying micronutrient imbalances. Over the last few decades, as farmers have intensified cropping cycles and adopted nutrient demanding varieties, these nutrient disorders have become even more pronounced, limiting both productivity and grain quality. This context underscores the need for complementary nutrient delivery strategies that can bypass the limitations of soil based fertilization.

2.2 Mechanisms of foliar nutrient uptake

Foliar fertilization addresses these constraints by delivering nutrients directly to the aerial parts of the plant, where they are absorbed more rapidly and with fewer losses compared to soil application. When nutrient solutions are applied to the leaf surface, they move through a series of steps that include wetting the cuticle, penetrating the epidermal cell wall, entering the apoplast, and subsequently moving into the symplast before being redistributed throughout the plant. These processes depend on several factors, including leaf age, cuticular characteristics, humidity, the chemical composition of the fertilizer, and the pH of the spray solution. Younger leaves generally exhibit higher absorptive capacity due to their thinner cuticular layers and greater physiological activity. Additionally, the absence of plasmodesmata between guard cells and epidermal cells influences the direction of nutrient flow, shaping the efficiency of translocation (Kannan, 2010) [18]. Although the biological pathways involved in foliar nutrient uptake are complex, the overall mechanism enables remarkably efficient nutrient absorption under favourable conditions.

2.3 Environmental conditions influencing foliar absorption

Weather conditions exert a strong influence on the effectiveness of foliar spraying. High humidity, moderate temperatures, and calm wind conditions promote longer droplet retention on the leaf surface and enhance cuticular hydration, which together improve nutrient absorption. These favourable conditions typically occur during the early morning and late evening, when stomata may also be partially open, promoting greater penetration of nutrient solutions into leaf tissues. In contrast, low relative humidity or high temperatures accelerate droplet evaporation, which can leave behind crystallized residues that reduce nutrient uptake efficiency. Strong wind speeds can further reduce the effectiveness of foliar application by causing uneven spray distribution or drift, while rainfall within 24 to 48 hours after spraying may wash away nutrients before they are adequately absorbed by plant tissues. Therefore, selecting an appropriate spraying window that aligns with optimal meteorological conditions is crucial to maximizing the effectiveness of foliar nutrition (Fernández and Eichert, 2009; Fernández *et al.*, 2014; Kannan, 2010) [10, 11, 18].

2.4 Characteristics of effective foliar fertilizers

The success of foliar fertilization depends not only on environmental conditions but also on the properties of the fertilizer itself. Effective foliar formulations must be highly soluble to ensure uniform coverage and penetration. Nutrient sources with low molecular weight, such as urea, tend to penetrate the leaf cuticle more efficiently than larger molecules or inorganic salts. The pH of the spray solution must be carefully adjusted, as excessively acidic or alkaline formulations can damage leaf tissues or precipitate nutrients before absorption. High purity materials are preferred in foliar applications to avoid residues that may clog nozzles or cause phytotoxicity on leaf surfaces. Nitrogen applied as urea is rapidly absorbed, while ammonium and nitrate forms exhibit slower uptake. Similarly, potassium nitrate, magnesium sulphate, and chelated forms of micronutrients such as zinc, iron, and manganese are commonly used due to their favourable absorption characteristics (Dordas, 2008; Moran, 2004) [9, 28]. Thus, fertilizer formulation plays a key role in ensuring both absorption efficiency and plant safety.

2.5 Agronomic role and benefits of foliar feeding in rice

Foliar nutrition provides several agronomic advantages, particularly in rice ecosystems where soil constraints frequently limit nutrient availability. By enabling direct entry of nutrients through leaf tissues, foliar feeding ensures a rapid physiological response, often visible within two to three days of application. It allows farmers to rectify nutrient deficiencies during critical stages such as tillering, panicle initiation, and grain filling, thereby improving chlorophyll content, photosynthetic efficiency, and overall plant vigour. Foliar sprays of macronutrients like nitrogen and potassium, as well as micronutrients such as zinc and iron, have been shown to enhance yield attributes including tiller production, grain filling, and thousand grain weight (Mohan *et al.*, 2017) [27]. Moreover, foliar application reduces nutrient losses from leaching or fixation, improving nutrient use efficiency and minimizing environmental impacts. This targeted approach is particularly valuable during abiotic stresses such as drought, salinity, or heat, when root uptake is impaired, and plants rely more on their foliar nutrient reserves. As a result, foliar feeding has emerged as an effective tool for improving crop resilience and stabilizing yields in rice based farming systems.

2.6 Timing and growth stage considerations

The timing of foliar nutrient application is a decisive factor in determining plant response. Rice plants exhibit different nutrient requirements at each growth stage, and their leaves possess the highest nutrient absorption capacity during periods of rapid expansion. Applications timed to coincide with maximum tillering, panicle initiation, and early reproductive development have been reported to produce the most favourable effects on physiological and agronomic traits. Research demonstrates that foliar application during multiple critical stages enhances plant height, chlorophyll concentration, leaf area index, grain setting percentage, and overall productivity (Mahmoodi *et al.*, 2020) [24]. Combined applications of nitrogen and micronutrients such as zinc have also been shown to improve grain quality parameters and nutrient density, especially when timed during flowering and milky stages (Tuiwong *et al.*, 2022) [44]. Proper synchronization of foliar sprays with plant developmental stages ensures efficient nutrient utilization and supports sustained yield improvement.

3. Advances in foliar fertilization approaches for enhancing rice growth, yield, and quality

3.1 Foliar use of conventional fertilizers and multinutrient NPK formulations

Early work on foliar fertilization in rice has largely focused on conventional fertilizers such as urea, diammonium phosphate (DAP), watersoluble NPK formulations, and their combinations with basal soil fertilization. Rani *et al.* (2014) [37] evaluated the effect of integrating foliar applied 19:19:19 NPK with soil applied recommended fertilizer doses in a field experiment under kharif conditions. Their study demonstrated that foliar supplementation of 19:19:19 at tillering and panicle initiation stages, in combination with basal NPK and additional muriate of potash (MOP) at panicle initiation, substantially increased grain yield, with the highest yield recorded in the treatment receiving recommended NPK plus foliar 19:19:19 and top dressed MOP. However, the economic analysis revealed that the benefit-cost ratio was highest when only the recommended dose of soil applied fertilizers was used, as additional foliar inputs increased costs. This highlights an important principle of foliar nutrition: while yield can often be enhanced with foliar supplementation, the economic optimum may depend on fertilizer prices and labour costs.

Similarly, Jagathjothi *et al.* (2012) [15] examined the integration of foliar applied DAP and urea phosphate with inorganic fertilizers and integrated nutrient management (INM) practices. Their results indicated that the combination of recommended INM plus repeated foliar sprays of urea phosphate at panicle initiation and ten days later produced the highest grain yields. From an economic standpoint, treatments combining 100% recommended inorganic fertilizers with 2% DAP or 2% urea phosphate sprays produced high net returns and favourable benefit-cost ratios, suggesting that foliar fertilization can significantly improve the profitability of rice cultivation when strategically combined with soil based nutrient management.

The role of phosphorus and zinc delivered through foliar sprays has also been investigated in Boro rice. Islam *et al.* (2024) [14] evaluated foliar supplementation of phosphorus and zinc in two rice varieties, BRRI Dhan 28 and BRRI Dhan 89, under different combinations of recommended fertilizer dose and foliar P and Zn. Their findings showed that foliar application of both 1% phosphorus and 0.5% zinc sulphate at panicle initiation markedly improved growth parameters and yield attributes, including panicle length, grains per panicle, thousand grain weight, and harvest index, particularly in BRRI Dhan 89. These observations corroborate the findings of Rafiullah *et al.* (2018) [34] and Boonchuay *et al.* (2013) [6], who reported improvements in panicle traits and biological yield with foliar phosphorus and zinc application. Taken together, these studies underline the importance of foliar NPK and phosphorus-zinc combinations as practical tools for enhancing yield components and overall productivity, especially when soil nutrient supply is inadequate or poorly synchronized with crop demand.

3.2 Potassium, secondary nutrients, and silicate based foliar nutrition

Potassium plays a key role in osmotic regulation, enzyme activation, and stress tolerance in rice. In sodic soils, where root uptake of potassium is frequently impaired, foliar application can provide an effective alternative. Jothi *et al.* (2019) [17] evaluated foliar sprays of different potassium salts—potassium chloride, potassium sulphate, and potassium nitrate applied at tillering, panicle initiation, and flowering. Their study showed that foliar application of 2% potassium nitrate consistently improved growth, yield, agronomic efficiency, and benefit-cost ratio compared to both other foliar treatments and soil applied potassium at 50 kg ha^{-1}. This suggests that foliar potassium, particularly as potassium nitrate, can partially substitute soil potassium under sodic conditions and offers a viable option where soil fertility or structure constrains root uptake.

Secondary nutrients, especially magnesium, are also suitable to foliar supplementation. George *et al.* (2018) [12] investigated different combinations of soil applied and foliar applied magnesium sulphate in direct seeded rice under farmers' field conditions in Kerala. Their results indicated that treatments combining moderate basal magnesium with subsequent foliar sprays at critical stages significantly improved yield attributes compared to basal application alone. Among the treatments tested, the combination of a modest soil dose of $MgSO_4$ at 20 days after sowing followed by a 2% foliar spray at 40 days after sowing produced the most favourable yield attributes, highlighting the value of integrating soil and foliar magnesium nutrition.

The use of potassium silicate as a foliar source of both potassium and silicon has also attracted attention due to its beneficial effects on plant structural integrity and stress tolerance. Shah *et al*. (2022) [40] evaluated different concentrations and timings of potassium silicate foliar spray in paddy. Their study demonstrated that higher concentrations applied at tillering, panicle initiation, and grain formation stages improved gross returns and benefit-cost ratio while simultaneously reducing pest incidence, lodging, and sheath mite infestation. The enhanced resistance was attributed to improved nutrient uptake and strengthened plant tissues, which together contributed to better resilience and yield performance. Silicon-based foliar sprays thus appear to offer dual benefits of nutrition and protective effects against biotic and abiotic stresses.

3.3 Micronutrients, nanonutrients, and grain quality improvement

Micronutrient deficiencies, particularly of zinc, iron, and boron, are widespread in rice growing regions and have direct consequences for both yield and nutritional quality of the grain. Foliar application is especially well suited for micronutrients because relatively small quantities are required and soil induced immobilization is common. Yogi *et al.* (2024) [51] investigated the effect of foliar application of zinc, copper, and boron alone and in combination on grain yield and harvest index. The combination treatment containing all three micronutrients (Zn + Cu + B) produced the largest leaf area index, the highest number of grains per panicle, the greatest thousand grain weight, and the highest grain and biological yields, clearly demonstrating the synergistic benefits of multi micronutrient foliar nutrition.

Foliar micronutrient application has also been shown to influence protein content and other quality parameters. Mohan *et al.* (2017) [27] reported that rainfed rice receiving the recommended dose of fertilizers together with foliar sprays of zinc, iron, boron, and sulphur produced significantly higher grain protein content compared with soil fertilization alone. Mahmoodi *et al.* (2020) [24] further showed that foliar sprays of a multinutrient liquid fertilizer containing N, P, K, Fe, B, Zn, Mn, and Cu at critical growth stages enhanced leaf chlorophyll concentrations by approximately 18% relative to untreated controls, signalling higher photosynthetic capacity.

The importance of foliar zinc application for seedling performance in zinc deficient soils was highlighted by Phuphong *et al.* (2020) [32]. They showed that foliar zinc sulphate markedly increased shoot and root dry weight and seedling zinc concentration in rice grown in zinc deficient calcareous soil, performing better than soil applied zinc under low zinc conditions. This suggests that foliar feeding can be particularly advantageous in soils with strong zinc fixation or high pH.

More recently, nano formulated micronutrients have been investigated as a means to increase foliar nutrient efficiency. Ugile *et al.* (2024) [45] compared soil and foliar applications of conventional zinc and iron sulphates with nano zinc and nano iron. They found that foliar application of a combination of nano zinc and nano iron along with recommended NPK produced the highest growth, grain yield, and seed quality, including improved starch content. Conventional soil applications of $ZnSO_4$ and $FeSO_4$ produced comparable but slightly lower starch content, indicating that nano formulated foliar nutrients may offer an efficiency advantage.

Efforts to biofortify rice grains with zinc through foliar fertilization are particularly noteworthy. Jose *et al.* (2021) [16] demonstrated that repeated foliar applications of zinc sulphate at specific growth stages, especially at maximum tillering and milking, significantly increased both grain yield and grain zinc concentration, outperforming basal soil zinc application alone. These findings provide strong support for the use of targeted foliar zinc sprays as a practical biofortification strategy to improve the micronutrient density of rice grain.

Recent field studies have further emphasized the role of foliar zinc and iron in enhancing nutrient uptake and grain nutritional quality. For instance, foliar Zn and Fe applications in transplanted rice during the reproductive stage have been shown to significantly increase grain Zn and Fe concentration while improving physiological efficiency and nutrient translocation, supporting the long term strategy of using foliar micronutrients for both yield stability and grain enrichment (Khan *et al.*, 2023) [19]. Similar results were reported by Das *et al.* (2024) [7], who observed substantial improvements in grain Zn concentration and plant nutrient uptake following foliar Zn supplementation under varying soil fertility conditions. These contemporary findings reinforce the global relevance of micronutrient foliar fertilization in overcoming widespread deficiencies in rice growing ecosystems.

3.4 Nano-fertilizers and integrated nutrient management

Nano-fertilizers have emerged as an important innovation in nutrient delivery, offering high surface area, improved penetration, and potential for reduced application rates. In rice, nano-urea and nano-DAP have been evaluated as foliar supplements within integrated nutrient management frameworks. Sahu *et al.* (2022) [38] examined different nitrogen management strategies and found that applying 50% of the recommended nitrogen dose as basal, combined with foliar sprays of nano urea at tillering and panicle initiation stages, significantly improved growth parameters, yield attributes, and nitrogen content in both grain and straw. This treatment also resulted in higher postharvest availability of N, P_2O_5, and K_2O in the soil, suggesting more efficient nutrient uptake and cycling.

Saud *et al.* (2022) [39] integrated liquid nano urea with soil test based fertilizer application and bio organic fertilizer in wet seeded rice. Their results indicated that the combination of 100% soil test based nitrogen, nano urea foliar sprays at critical stages, and bio organic fertilizer produced the highest grain yield, plant height, number of productive tillers, and benefit-cost ratio. The authors suggested that organic mineral associations formed by bio organic fertilizer may have reduced nitrogen losses and improved nitrogen availability throughout the crop growth period, while foliar nano urea enhanced nitrogen absorption and assimilation.

Nano-phosphorus fertilization has also been explored. Deo *et al.* (2022) [8] evaluated nano-DAP as a partial substitute for conventional phosphorus in rice. Treatments combining reduced soil applied phosphorus (50% of the recommended dose) with root dipping and two foliar sprays of nano-DAP produced higher grain and straw yields than full soil applied phosphorus alone. The enhanced nutrient uptake observed in nano-DAP treatments was attributed to improved penetration and mobility of nano sized particles in plant tissues.

Nandy *et al.* (2023) [30] further extended nanonutrient research by integrating nano zinc foliar sprays within different nitrogen management regimes involving combinations of inorganic fertilizers and farmyard manure. Their findings showed that the highest grain and straw yields were obtained when 75% of nitrogen was supplied through inorganic fertilizers and 25% through farmyard manure, combined with foliar nano zinc. This points to the potential of nano micronutrients as part of integrated nutrient management strategies that combine mineral fertilizers with organic amendments for improved productivity and soil health.

Emerging research also highlights the importance of foliar fertilization in reducing soil applied nitrogen without compromising yield. A 2023 study demonstrated that strategic foliar spraying of nitrogen at critical growth stages enabled a reduction of basal soil nitrogen while maintaining grain yield and improving nitrogen use efficiency in high quality rice cultivars (Li *et al.,* 2023) [23]. This aligns with the broader movement toward low input, high efficiency nutrient management systems and positions foliar nutrition as an integral tool in sustainable nitrogen management.

3.5 Organic foliar sources and bio organic inputs

In addition to inorganic and nano fertilizers, a growing body of research has explored organic foliar inputs such as amino acid formulations, vermiwash, panchagavya, dasagavya, and bio organic fertilizers. These inputs often act as biostimulants, influencing not only nutrient status but also physiological processes and soil plant interactions.

Mirtaleb *et al.* (2021) [26] evaluated foliar applications of amino acids and potassium, alone and in combination, and observed increased concentrations of mineral nutrients, protein, and amylose in both brown and milled rice, with the amino acid plus potassium treatment producing the highest essential and non essential amino acid contents in brown rice. This suggests that amino acid based foliar solutions can enhance grain nutritional quality beyond simple yield improvements.

Priyanka *et al.* (2019) [33] examined the influence of fish amino acid and egg amino acid foliar sprays applied at tillering, panicle initiation, and flowering, in combination with recommended fertilizer doses, under sodic soil conditions. Their results showed that integrating egg amino acid at 1.0% with the recommended dose of fertilizers significantly improved physiological parameters such as leaf area index, crop growth rate, total chlorophyll, and soluble protein, resulting in higher yields. Similar work on indigenous organic preparations has shown promising effects. Upadhyay *et al.* (2018) [46] reported that panchagavya, applied through root dipping, foliar sprays, and irrigation water, in combination with 100% recommended fertilizer dose, markedly increased grain yield in transplanted rice. Raman and Krishnamoorthy (2019) found that foliar application of vermiwash at 6% produced the highest number of tillers, dry matter accumulation, panicle number, and grain yield, followed closely by panchagavya at 6%, indicating that certain organic foliar formulations can effectively enhance rice growth and productivity.

Kumarimanimuthuveeral and Sathiya (2014) [20] further demonstrated that combining pressmud, recommended fertilizers, and biofertilizers with repeated foliar sprays of dasagavya significantly increased rice yields across seasons, underscoring the potential of integrated organic nutrient management. These studies collectively suggest that organic foliar sources, when scientifically formulated and appropriately timed, can function as effective biostimulants that complement conventional fertilizers in rice cultivation.

Recent review literature also supports the role of foliar nutrition as a supplemental strategy rather than a primary fertilization method. A comprehensive 2022 synthesis on foliar Zn application in rice concluded that foliar sprays especially when combined with soil Zn, enhance grain Zn accumulation, grain filling, and biomass production (Rahman *et al.*, 2022) [36]. This review also emphasized that the timing and frequency of foliar sprays are critical in determining the magnitude of biofortification.

3.6 Foliar silicon nutrition, soil parameters, and advanced application technologies

Silicon nutrition, particularly through foliar application, has been studied for its ability to mitigate metal toxicities and enhance stress tolerance in rice. Nagula *et al.* (2016) [29] investigated the application of silicon and boron as soil and foliar treatments in laterite derived wetland rice soils of northern Kerala. Their study revealed that calcium silicate and potassium silicate, especially when applied as foliar sprays in combination with borax, significantly reduced available iron, manganese, and exchangeable aluminium in the soil and increased grain and straw yield. This indicates that silicon based foliar sprays can play an important role in alleviating Fe, Mn, and Al toxicity in problem soils while simultaneously improving rice productivity.

Foliar nutrition can also influence soil chemical and biological properties when integrated with broader nutrient management practices. Lekshmi (2018) [22], working in the Kuttanad region, reported that combining soil amelioration practices and soil test based fertilization with customized foliar nutrient sprays significantly increased rice yield and improved selected soil parameters compared to conventional fertilization alone. These findings reinforce the view that foliar nutrition should be considered part of an integrated nutrient management strategy rather than as a stand-alone intervention.

Recent work has also emphasized the role of improved application technologies. Xu *et al.* (2021) [50] compared conventional manual spraying with unmanned aerial vehicle (UAV) assisted foliar zinc fertilization. Over three years, they showed that UAV based spraying of a higher concentration zinc glycine formulation at fewer application events achieved zinc biofortification levels comparable to or better than repeated manual sprays with a lower concentration zinc nitrate solution. Importantly, UAV spraying reduced zinc input, improved zinc recovery, and lowered the risk of fertilizer residues in rice paddies. This demonstrates that advanced application technologies can enhance the efficiency, safety, and scalability of foliar nutrition in rice production.

Beyond zinc and iron, recent studies have explored the potential of multimicronutrient foliar sprays containing Zn, Fe, I, and Se to improve the nutritional profile of rice grains. Se based foliar sprays, in particular, have shown promise for increasing grain Se concentration without yield penalties, and when applied alongside Zn or Fe, they enhance the overall micronutrient density of rice grain (Wang *et al.*, 2023) [49]. Such multielement foliar approaches are gaining traction as holistic biofortification strategies aimed at addressing multiple nutrient deficiencies simultaneously in human populations.

3.7 Growth regulators, stress mitigation, limitations, and toxicity concerns

Beyond nutrients, foliar application of plant growth regulators in combination with fertilizers has been explored as a means to improve grain quality and mitigate environmental stresses. Okasha *et al.* (2019) [31] evaluated foliar sprays of DAP, potassium, nitrogen-potassium mixtures, gibberellic acid plus potassium, salicylic acid plus potassium, and humic acid plus potassium at panicle initiation and mid-booting stages. Their study showed that treatments involving humic acid with potassium, and gibberellic acid with potassium, improved grain quality traits, including amylose content and reduced proportion of broken grains, likely through enhancements in photosynthesis, assimilate translocation, and grain filling.

Raghunath *et al.* (2021) [35] studied the impact of foliar applied plant growth regulators and nutrients on rice exposed to high temperature stress under controlled conditions. They reported that the combined application of phytohormones and nutrients improved physiological parameters such as cell membrane stability, photosynthetic rate, stomatal conductance, and chlorophyll fluorescence (Fv/Fm), while reducing leaf temperature and transpiration. These improvements translated into better yield performance under heat stress, illustrating the potential of foliar based stress mitigation strategies in the context of climate change.

Despite these benefits, foliar fertilization has inherent limitations and risks. It is generally more effective for meeting micronutrient demands than for supplying large quantities of macronutrients, and its success depends heavily on suitable meteorological conditions. Responses to foliar nutrition are often transient, and over application or excessively high concentrations can cause leaf scorching and other phytotoxic effects. Water soluble foliar fertilizers are typically more expensive than conventional granular forms, which may limit their adoption unless yield or quality gains clearly offset additional costs.

The risk of toxicity from high foliar doses is exemplified by the work of Akila *et al.* (2019) [1], who evaluated increasing levels of copper applied to soil and as foliar $CuSO_4$ sprays. Their results showed that foliar copper concentrations above 0.25% reduced grain and straw yields, likely due to copper toxicity leading to chlorophyll degradation and inhibited photosynthesis. Such findings highlight the importance of adhering to recommended concentrations, carefully calibrating spray solutions, and considering both crop safety and environmental impact when designing foliar fertilization programs.

Chelated micronutrients have been identified as a promising next generation foliar source due to their enhanced stability, higher uptake efficiency, and improved plant mobility compared to conventional salts. Studies using Zn-glycine and Fe-EDTA chelates have reported greater micronutrient translocation to grains with fewer required spray events, suggesting that chelated formulations may help reduce input costs while improving foliar efficiency (Huang *et al.*, 2022) [13]. Such formulations represent an important direction for future foliar nutrition research, particularly in regions with severe micronutrient fixation in soils.

4. Limitations and future directions for foliar nutrition research in rice

Foliar nutrition is an effective supplementary strategy in rice cultivation, but several limitations restrict its full potential. Foliar sprays cannot meet the complete macronutrient requirement of rice and are highly dependent on favourable environmental conditions for effective absorption. Excessive concentrations may also cause leaf scorching or micronutrient toxicity, and uneven spray distribution in large fields can reduce efficiency. Additionally, the cost of high-purity, water-soluble fertilizers may limit adoption among smallholder farmers.

Despite these constraints, future advancements offer considerable promise. Research on nano-fertilizers, slow-release foliar formulations, and multinutrient blends may improve nutrient delivery, uptake efficiency, and the duration of nutrient availability. The integration of precision agriculture tools such as drone based smart spraying, crop sensors, and data driven decision models can enable site specific foliar application and reduce nutrient wastage. Enhancing abiotic stress tolerance through foliar biostimulants and developing eco-friendly and organic foliar inputs will support sustainable rice production. Foliar biofortification with micronutrients such as zinc, iron, selenium, and iodine remains a promising avenue to improve grain nutritional quality and address dietary deficiencies. Strengthening farmer training and regulatory support will be essential for the wider adoption of improved foliar technologies. Collectively, these innovations can enhance the role of foliar nutrition in resilient, efficient, and high quality rice production systems.

5. Conclusion

Foliar nutrition represents a versatile and increasingly important tool in modern rice cultivation. It serves as a rapid and efficient method for delivering agrochemicals including fertilizers, pesticides, biostimulants, and nanoformulated inputs directly to plant foliage, thereby bypassing soil-related constraints such as fixation, leaching, and nutrient immobilization. Its advantages include rapid correction of nutrient deficiencies, minimal nutrient loss, enhanced physiological responses, and the potential to improve both yield and grain quality. In addition, foliar sprays play a crucial role in biofortifying rice grains with essential micronutrients, thereby contributing to nutritional security.

However, foliar nutrition is best viewed as a complementary strategy rather than a replacement for soil fertilization. While highly effective in supplying micronutrients and correcting acute deficiencies, it cannot alone meet the full macronutrient requirements of rice crops. The future of foliar nutrition lies in the development of innovative formulations, precision delivery technologies, ecofriendly solutions, and integrated nutrient management practices. By aligning these advancements with climate smart and sustainable agriculture principles, foliar nutrition can significantly contribute to improving rice productivity, resilience, and nutritional value, ultimately supporting global food security.

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