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Foliar fertilization for nutrient use efficiency

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Abstract
Foliar fertilization, the direct application of nutrients onto plant leaves, has emerged as a complementary practice to soil fertilization for improving nutrient uptake, crop growth, and yield performance. Nutrients applied through foliar sprays penetrate the cuticle and stomata, allowing rapid absorption into plant tissues, which is particularly useful for correcting deficiencies of secondary and micronutrients such as zinc, iron, manganese, and boron, and for supplementing macronutrient needs during critical growth stages. Research findings highlight that foliar spraying in raised bed systems increased rice yield by 9.33% compared to conventional flat planting, while reducing irrigation water usage by 39% and enhancing water use efficiency. Agronomic efficiency of fertilizers was also significantly improved, with foliar spray on raised beds achieving 93.82% compared to 43.67% under broadcasting. Similarly, zinc-based foliar treatments improved grain yield, total dry matter, 1000-grain weight, protein content, and nutrient accumulation in both grain and flag leaves. In wheat, foliar application of nano-fertilizers, particularly Nano Chelated Super Fertilizer (NCSF), alone or in combination with potassium and amino acids, produced significant improvements in biological yield, grain yield, harvest index, and agronomic efficiency compared to control plots. The combined use of dual and triple nano formulations further enhanced nutrient uptake and crop productivity, demonstrating the potential of nano-based foliar fertilization to address nutrient limitations and improve efficiency. Overall, foliar fertilization, especially with nano formulations, not only supplements soil fertilization but also improves nutrient use efficiency, mitigates abiotic stress effects, and supports sustainable intensification of cereal production under varied agro-ecological conditions.

keywords: Foliar fertilization, nano fertilizers, nutrient use efficiency, crop yield

Introduction

Foliar Fertilization

Foliar fertilization is the practice of delivering mineral nutrients to plants through their leaves rather than the soil, directly onto the leaves of plants through foliar spraying, serving to supplement conventional soil-based fertilization methods. The emphasis is on utilizing foliar treatments to enhance the absorption and utilization of nutrients are already available in the arable land, rather than relying on foliar inputs as the exclusive source of plant nourishment. An effective nutrient management strategy begins with comprehensive soil-based fertilization, which relies on robust soil analysis techniques as described by Westermann (1990) [9]. Once initial soil fertility is established, subsequent deficiencies in plant nutrition can be accurately identified through tissue analysis, such as that outlined by Sabbe and Hodges (2009) [8], and rectified with additional soil or foliar applications as appropriate. A wide variety of water-soluble fertilizer nutrients can be efficiently delivered to the aerial tissues of plants; after application, these nutrients penetrate plant leaves via the cuticle or stomatal openings, eventually entering plant cells where they participate in metabolism

In foliar feeding, fertilizers are delivered to plants through direct spraying on their leaves, allowing essential nutrients to be absorbed through the leaf surfaces. Plants uptake these nutrients via their stomata as well as the epidermis, which facilitate water absorption. In foliar spaying, nutrients dissolved in water are delivered directly to plant foliage ensuring quick absorption and utilization. In addition, this practice can provide essential macronutrients during periods of limited soil moisture when root absorption is restricted. However, foliar application is regarded as a supplementary practice and not a substitute for soil fertilization. In recent years, foliar feeding has gained significant recognition for its role in enhancing crop productivity, notably in horticultural species. While its adoption in major agronomic crops is less extensive, the documented benefits of foliar fertilization are compelling, and efforts to establish more consistent and reliable crop responses continue to progress.

Nutrient Assimilation Pathway under Foliar Application

For foliar fertilization to be effective, nutrients must penetrate the leaf surface, cross the cuticle and epidermal cell membrane, and reach the cytoplasm where they support metabolic functions and growth. This pathway resembles nutrient uptake through roots, but the cuticle is the major barrier to efficient absorption.

Foliar feeding is not intended to substitute soil fertilization, as soil application remains the most reliable and economical means of meeting a plant's primary nutrient requirements, particularly nitrogen, phosphorus, and potassium. Instead, foliar application is especially effective for supplying secondary nutrients such as calcium, magnesium, and sulphur, along with micronutrients including zinc, manganese, iron, copper, boron, and molybdenum. It can also complement N- P- K nutrition during short or critical growth phases. A major function of foliar feeding is to delay senescence by enhancing nutrient translocation to developing seeds, fruits, tubers, or vegetative organs when photosynthesis declines and root activity diminishes. Moreover, foliar feeding acts as a strategic measure during pre-reproductive stages to counter environmental stresses and poor nutrient availability, thereby supporting regrowth, extending the growth period, and optimizing yield potential.

Foliar feeding offers two primary benefits regarding crop response: (1) it provides a highly efficient and timely delivery of essential or critical nutrients and (2) it compensates for nutritional shortfalls arising from soil or environmental limitations.

Ideal Application for Foliar Nutrition

Proper Growth Stage: A crucial aspect of an effective foliar feeding strategy is the precise timing of nutrient applications, which should coincide with the specific developmental stages of the plant during which yield potential is established. Delivering essential nutrients within this critical window positively influences subsequent post-reproductive growth phases, optimizing crop productivity. Irrespective of the crop's present nutrient condition, applying several small-dose foliar sprays during critical stages proves most advantageous. Close observation of crop developmental phases, often weekly or even daily, is essential to decide the right moment for such applications. In addition, thorough plant tissue testing just before spraying helps identify which nutrients most restrict growth. Interpreting these test results through the Diagnosis and Recommendation Integrated System (DRIS) provides a clear ranking of nutrients from most to least limiting, thereby ensuring accurate nutrient management in line with crop needs.

Proper Crop Condition: Generally, crops that possess sound nutritional status tend to exhibit a more robust response to foliar feeding. This enhanced responsiveness is largely due to improved tissue quality, which facilitates maximal nutrient absorption by the leaves and stems, as well as increased growth vigor, enabling rapid translocation of nutrients throughout the plant. Conversely, crops subjected to heat or moisture stress often demonstrate diminished leaf and stem absorption capacities and reduced vigor, thereby leading to a decreased efficacy of foliar treatments. Nonetheless, foliar feeding administered prior to the onset of such abiotic stresses can positively influence crop performance and productivity. Appropriately applied foliar sprays also have the potential to expedite recovery from adverse growth conditions, including cold stress and herbicide damage. For example, foliar application of nitrogen-sulphur solutions facilitated significant recovery in corn plants damaged by light to moderate hail. Although advantageous, the effectiveness of foliar nutrition as a corrective measure is largely restricted by practical and economic constraints on the quantity of nutrients that can be feasibly delivered through foliar sprays to produce a positive growth response.

Proper Meteorological Conditions: The performance of foliar applications is strongly influenced by environmental conditions such as time of application, air temperature, humidity, and wind velocity, as these factors govern both the physical and physiological processes of nutrient uptake. A key factor in foliar absorption is the ability of nutrients to penetrate leaf tissues, which is most effective under warm, humid, and still weather. Such conditions, typically occurring in the late evening or occasionally early morning, increase tissue permeability and thereby improve nutrient use efficiency. The referenced table outlines the specific climatic conditions that are most favourable for successful foliar spraying.

Weather Parameters Conducive to Foliar Sprays

Time of Day	**Late evening; after 6:00 p.m.**
	Early morning; before 9:00 a.m.
Temperature	Low temperature 18-19 °C (Ideal 21 °C)
Humidity	Greater than 70% relative humidity
Wind speed	less than 5 mph
Time of Day	Late evening; after 6:00 p.m.
Rainfall	Within 24 to 48 hours after a foliar application may reduce the application effectiveness, as not all nutrient materials are immediately absorbed into the plant tissue.

Key desirable characteristics of foliar fertilizers include the following:

1. **Solubility:** Foliar fertilizers must be readily dissolvable or dispersible in water and should include an active chemical form, such as salts, chelates, or nutrient complexes, to guarantee efficient nutrient supply.
2. **Molecular Weight/Size:** To facilitate penetration through the leaf cuticle, the molecules in foliar fertilizers must have a low molecular weight or be sufficiently small in size.
3. **Solution pH:** The pH of the foliar fertilizer solution should be carefully adjusted to optimize nutrient activity while minimizing the risk of phytotoxicity, such as leaf scorching or burning.
4. **Chemical Form:** Ammonium ions exhibit higher absorption rates through leaves compared to nitrate ions. Urea is particularly effective in penetrating leaf tissues more readily than other inorganic nitrogen fertilizers. By contrast, potassium chloride (KCl), which rapidly crystallizes on leaf surfaces, is better suited for soil application and is generally unsuitable for foliar use.

Forms of Fertilizer Inputs/Amendments/Carriers

- **Fertilizer Compounds:** Not every form of fertilizer is suitable for foliar use. The main purpose of foliar feeding is to enhance the direct uptake of nutrients through plant tissues, which requires that fertilizer formulations meet certain standards to avoid leaf injury. Essential characteristics of appropriate fertilizer compounds include:
- **Low salt index:** High salt concentrations, particularly from nitrates (NO3-) and chlorides (Cl-), can cause significant cellular damage in plant tissues.
- **High solubility:** Fertilizer materials need to be highly soluble to minimize the volume of solution required for effective application.
- **High purity:** Fertilizers must exhibit high purity to avoid complications such as interference with spray delivery, incompatibility with other solution components, or unintended negative effects on the foliage.

Fertilizer materials

A) **Nitrogen Materials:** Nitrogen Sources for Foliar Feeding: Among the various nitrogen fertilizers, urea is regarded as the most efficient for foliar use because of its high solubility and comparatively low salt index. Urea also increases leaf tissue permeability, thereby promoting the uptake of not only nitrogen but also other essential nutrients. However, for foliar spraying, the urea applied should contain a biuret content of 0.2% or less to reduce the likelihood of leaf injury from urea toxicity. Modern urea-based liquid formulations and feed-grade products generally maintain sufficiently low biuret levels to avoid damage. In addition to urea, other nitrogen fertilizers suitable for foliar application include ammonium polyphosphates, liquid ammoniated ortho-phosphates, ammonium thiosulfate (12-0-0-26S), and liquid ammonium sulphate (8-0-0-9S). Another option is triazine, a slow-release nitrogen compound discovered in the late 1970s, which is considered effective for foliar spraying due to its lower risk of leaf scorching. Research comparing triazine with urea, ammonium, and nitrate sources has shown that it reduces leaf burn while improving nitrogen uptake through foliage. Triazone is commercially available under trade names such as N-Sure® (28-0-0) and Trisert® (20-0-0-0.5B; 13-3-4; 13-3-4-0.3B), produced by Hickson Kerley, Inc., Phoenix, Arizona.

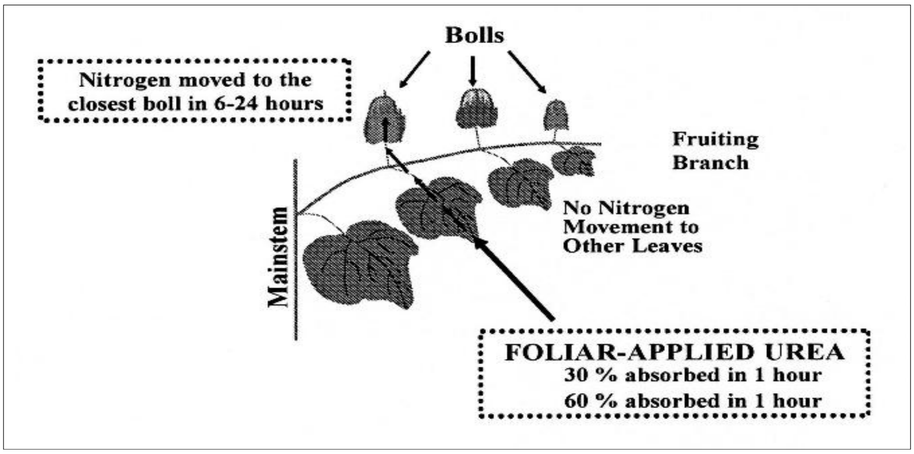

Fig 1: The uptake of foliar-applied N labelled urea by a leaf on a cotton branch and subsequent movement to the closest developing boll (Redrawn from Miley and Oosterhuis, 1989).

B) Phosphorus Materials: The risk of leaf burn is reduced, and phosphate absorption by leaves is enhanced when a combination of polyphosphates and orthophosphates is applied. This benefit may be attributed to the simultaneous delivery of both ortho- and polyphosphate forms, which improves nutrient uptake efficiency.

C) Potassium Sources: Potassium polyphosphates are considered a highly effective potassium fertilizer, noted for their low salt index and good solubility, depending on accessibility. Although potassium sulfate has a low salt index, its limited solubility reduces efficiency, yet it is still usable for foliar spraying. Other potassium forms, including potassium hydroxide, potassium nitrate, and potassium thiosulfate, combine low salt indices with high solubility, making them well-suited for foliar nutrition.

D) Secondary and Micronutrient Sources: Foliar feeding of secondary nutrients (calcium, magnesium, sulphur) and micronutrients (zinc, manganese, iron, copper, boron, molybdenum) can be highly effective in improving plant nutrition. However, certain elements—especially calcium, magnesium, iron, boron, and molybdenum—often face challenges in absorption and movement within the plant. Therefore, choosing the right fertilizer form is essential. While chelated compounds are useful for soil application, they are generally less suitable for foliar sprays because the relatively large size of most chelating agents limits their penetration into leaf tissues. The efficiency of foliar uptake of secondary and micronutrients can be improved by employing organic chelating agents such as citric acid, malic acid, amino acids, phenolic acids, glucoheptonate, and glucosylglycine.

Advantages of Foliar Nutrition

- Foliar sprays can be combined with other treatments such as insecticides, enhancing operational efficiency.
- Foliar application is particularly beneficial when soil nutrient availability is deficient.
- It provides a rapid growth response when timely nutrient delivery is critical.

- Foliar sprays can be applied to address high fixation rates of phosphorus and potassium in soils.
- It is useful for managing adverse field conditions including root rot disease and drought stress.

Limitations

- Excessive spray concentrations may cause leaf scorching or blistering.
- Use of sticking agents is often necessary to improve adherence and efficacy.
- Large leaf areas need to be covered to achieve desirable nutrient uptake efficiency.
- Only relatively small quantities of fertilizer can be applied via foliar methods.
- The effectiveness of foliar fertilization is strongly influenced by environmental factors such as temperature, humidity, and wind speed.
- Multiple applications, though sometimes necessary, can be economically prohibitive.
- There is always a risk of foliar burn when high concentrations of nutrients are applied.

Table 1: Grain yield and yield components with respect to foliar spray in bed and conventional method

	Yield and yield components			
Method of Fertilizer application	**Grain yield (tha^{-1})**	**Panicles m^{-2} (no)**	**Grains panicle^{-1} (no)**	**1000-gram wt (gm)**
Foliar spray fertilizer in raised bed	4.68	298a	165a	23.10
Fertilizer broadcasting in conventional planting	4.37	276b	140b	22.88
LSD at 5%	0.26	3.34	4.98	1.32
Level of Significance	n.s.	**	**	n.s.

Where ** represents probability of <_0.01 and n.s. represents probability of >0.05. Values were means of three replicates. In a column figures with same letter do not differ significantly whereas figures with dissimilar letters differ significantly (*P*<_0.01).

Table 2: Agronomic efficiency of fertilizer by foliar spray in bed and conventional plot

Method of Fertilizer application	Agronomic efficiency (%)
(i) Foliar spray of fertilizer in raised bed	93.82
(ii) Fertilizer broadcasting in conventional planting	43.67
LSD at 5%	5.26
Level of significance	**

Where ** represents probability of <_0.01. Values were means of three replicates. In a column figure with same letter do not differ significantly whereas figures with dissimilar letter differ significantly (*p*<_0.01) Frageria.,(2009) [1].

Recent research demonstrated that foliar spraying on raised beds increased rice yields by 9.33% compared with conventional flat field tillage. The use of raised beds also led to a 39% reduction in irrigation water consumption and improved overall irrigation efficiency. The study concluded that water use efficiency for both grain and biomass production was higher when foliar fertilizers were applied in raised bed systems versus traditional flat planting. Furthermore, the agronomic efficiency of foliar-applied fertilizers in raised beds was substantially greater than in conventional methods, likely due to enhanced crop management associated with bed planting. Raised beds also alleviated soil surface crusting and improved soil physical properties relative to flat fields. High-yielding Aman rice, which relies on both rainfall and supplemental irrigation, was successfully grown under these conditions during the trial period, although further validation is required. Current investigations are focusing on evaluating the growth and yield performance of transplanted boro rice, which depends entirely on irrigation, under foliar spray and conventional fertilizer treatments in both raised bed and flat planting systems.

Table 3: Means Comparison of cultivars and various treatments for yield, growth indices, accumulation Zn and Fe in grain and leaf

Characters	Tajan	Nye-60	Zn0	Znl	Zn2	Zn3	LSD (5%)	CV (%)
Grain yield (g)	11.89b	12.53a	11.31c	12.02b	12.68ab	12.83a	0.78	6.76
Total dry matter (g)	26.01a	27.48a	23.96b	26.42ab	27.62a	28.99a	2.24	5.16
1000 grain weight	45.39b	50.68a	45.05b	47.47ab	49.50a	50.11a	3.63	6.11
Harvest index	0.46a	0.46a	0.47a	0.46a	0.46a	0.44a	0.06	3.59
No. of tillers	16.42a	14.42b	13.00c	14.50bc	16.00b	18.17a	2.12	11.13
Grain Zn content (ug g^{-1})	59.42a	54.08b	45.45b	52.08b	62.20a	67.27a	7.63	10.84
Flag leaf Zn content (ug g^{-1})	272.50a	271.11a	58.58d	150.00c	365.17b	513.67a	61.38	11.24
Height (cm)	65.24a	64.10a	61.51b	64.89a	65.32a	66.97a	3.28	4.10
Spike length (cm)	10.22a	10.10a	9.94a	10.06a	10.32a	10.29a	0.76	4.29
Awn length (cm)	6.52a	6.36a	6.60a	6.42a	6.30a	6.39a	0.68	11.26
Flag leaf length (cm)	19.23a	21.68a	18.83a	19.99a	21.07a	21.93a	6.14	12.15
Flag leaf width (cm)	1.47a	1.53a	1.44a	1.44a	1.55a	1.58a	0.20	7.48
No. of nodes	4.03a	4.11a	3.77c	4.06b	4.16ab	4.29a	0.20	3.97
Protein content (%)	18.86a	18.06b	17.94c	18.40bc	18.53ab	18.97a	0.47	2.08
Grain Fe (ug g^{-1})	39.35a	37.26a	34.09b	37.42ab	42.06a	39.63a	4.71	9.94

Zn0 = no zinc fertilizer, Zyl= 5kg Zn ha^{-1} in soil + 300g Zn ha^{-1} in foliar application, Zn2 = 10kg Zn ha^{-1} in soil + 600g Zn ha^{-1} in foliar application and Zn3 = 15 kg ha^{-1} in soil + 900 ha^{-1} in foliar application. Different letter(s) in each row and in each treatment show a significant difference (<0.05)

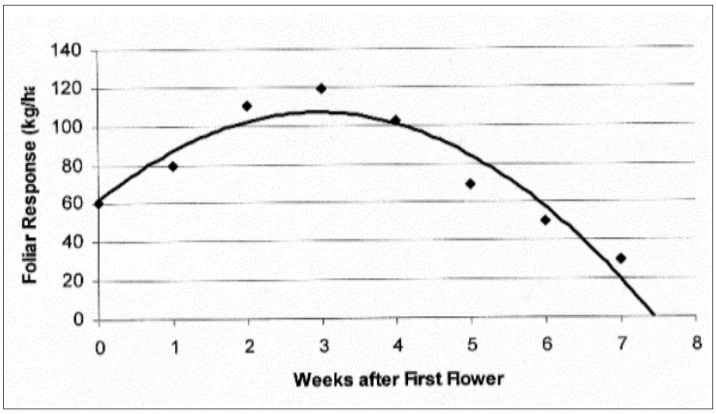

Fig 2: Standard crop response to foliar-applied potassium at different intervals following the onset of flowering (adapted from Weir and Roberts, 1993) ($y = 67.4 + 29.86x - 5.26x^2$, $R = 0.979$, $p = 0.03$).

Table 3: Nano fertilizer properties

Type of nano fertilizer	Symbol	Contains of Nutrients%	Origin
Chelated Super Fertilizer	NCSF	N6,P3,K17,Mg3,Ca1,S6Fe4,Zn4, Mn2,Cu0.5,B0.5,Mo0.1	Iranian
Potassium Fertilizer	NK	27	Iranian
Amino acids	AA	Aminoacids	Turkish

Table 4: Treatments

Tr. No	Treatments of foliar nutrition	Dates and rates of foliar nutrition treatments combinations (ml or gm in 100 L^{-1} water)	
		120 DAP	134 DAP
T_1	Control (spray with water only)	0	0
T_2	Nano (NK)	100	150
T_3	Nano (AA)	100	150
T_4	Nano (NCSF)	100	150
T_5	Nano (AA+NK)	50+50	75+75
T_6	Nano (NCSF+NK)	50+50	75+75
T_7	Nano (NCSF+AA)	50+50	75+75
T_8	Nano (NCSF+AA+NK)	33.33+33.33+33.33	50+50+50

Table 5: Impact of Foliar Application of Nano-Fertilizers and Amino Acids on Biological Yield and Grain Yield (Mg ha^{-1}), 1000-Grain Weight (g), Harvest Index (%), Grain Protein Content (%), and Agronomic Efficiency (kg kg^{-1})

Tr. No	biological yield Mg ha^{-1}	grain yield Mg ha^{-1}	weight of 1000 g	harvest index%	Protein%	Yield (Kg kg -1)
T1	12.649	4.466	40.78	35.37	10.44	466
T2	13.352	5.033	42.55	37.70	12.33	620
T3	13.518	5.375	44.56	39.78	13.00	698
T4	13.694	5.836	46.99	42.62	13.88	809
T5	13.941	5.718	46.44	41.02	13.55	774
T6	14.352	6.206	48.63	43.25	13.95	866
T7	14.700	6.596	49.28	44.87	14.22	938
T8	15.435	7.036	50.43	45.59	14.44	101
$LSD_{0.05}$	0.039	0.10040	0.550	1.245	0.101	16

Juthrey, (2019).

The research revealed that foliar application of Nano-Chelated Super Fertilizer at 1 kg ha^{-1} produced the best results in terms of wheat growth, grain yield, nutrient absorption, and agronomic efficiency. Among the treatments, the combined use of dual and triple nutrients along with a bio stimulant showed the most pronounced improvements in growth and yield traits of wheat under Iraqi conditions compared with the untreated control.

Conclusion

Foliar feeding has emerged as a vital strategy for enhancing crop productivity, particularly for crops that rely mainly on their leaves for nutrient uptake. In several instances, supplying nutrients through the foliage is the most practical approach for delivering certain elements. Foliar fertilization is relevant for nearly all crops at different growth stages and is increasingly adopted as a preventive strategy to address specific nutrient deficiencies and reduce the risks posed by unpredictable adverse weather during crop development. Importantly, foliar sprays should not be applied solely in response to confirmed nutrient deficiencies, as declines in yield and quality often precede the visible symptoms of deficiency. Instead, similar to soil-applied fertilizers, foliar nutrient applications should be used proactively to maintain crops at an optimal rather than marginal productivity level.

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