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Foliar Nutrition in Modern Agriculture: Advances, Precision Applications, and Sustainable Strategies

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Introduction

Foliar feeding enables targeted delivery of macro- and micronutrients to crop canopies, improving plant nutrition at critical growth stages and correcting soil-based deficiencies quickly. Historically, foliar sprays have been prized for correcting micronutrient shortages (e.g., Zn, Fe, B, Mn) and for quality improvements in fruits and vegetables, but recent years have seen rapid innovation that broadens their role. Modern drivers include the need to increase nutrient use efficiency (NUE), reduce losses from soil applications, mitigate abiotic stress impacts, and align with precision-agriculture goals [1,2].

Nano fertilizers and controlled-release foliar products

Nano fertilizer research has expanded rapidly, with foliar application emerging as a promising delivery route. Nano-formulations (e.g., metal-oxide nanoparticles, polymer-encapsulated nutrients, chitosan carriers) enhance leaf penetration because of small particle size, high surface area, and possible interaction with cuticular pathways. Multiple greenhouse and field studies report improved uptake, increased fruit or grain quality, and sometimes higher yield when nano-enabled foliar products are used compared to conventional sprays [2-4]. However, efficacy can be crop- and formulation-specific; small plot gains do not always scale directly to farm systems. Environmental fate and ecotoxicology remain active concerns; recent syntheses call for long-term monitoring and harmonized testing protocols before wide scale commercialization [4].

Foliar bio stimulants, amino acids, and microbial products

Protein hydrolysates, free amino-acid formulations, seaweed extracts, humic substances, and certain microbial inoculants applied foliarly have been shown to modulate plant physiology, improve antioxidant defenses, and support nutrient assimilation during stress episodes. Meta-analyses and recent trials indicate benefits for drought and salt tolerance, enhanced fruit quality, and improved canopy recovery after heat events [3-6]. Mechanistically, these products appear to act through signalling pathways (e.g., hormone modulation), osmoprotection, and stimulation of antioxidant enzyme systems, though mode-of-action studies are still consolidating.

Integration with precision agriculture and application technology

Advances in low-altitude remote sensing (multispectral, hyperspectral, LiDAR) and AI-driven decision tools now allow more precise timing and spatial targeting of foliar applications. UAV-mounted sprayers with variable-rate spraying (VRS) and LiDAR height correction are being tested and deployed to improve spray uniformity, reduce drift, and apply foliar inputs only where crop indices indicate need [5,7]. Such systems reduce input use and can improve efficacy by matching application windows to canopy development and crop stress signals.

Mechanisms of uptake and limiting factors

Foliar uptake pathways include cuticular diffusion, stomatal uptake, trichome interactions, and possible endocytic processes for nanoparticulates. Key determinants are: solute chemistry (ionic vs chelated forms), pH and ionic strength of spray solution, molecular size, droplet size and deposition pattern, presence of surfactants/adjuvants, and leaf surface properties (wax composition, trichome density). Environmental variables solar radiation, temperature, humidity, and wind, affect stomatal

opening and droplet evaporation and thus uptake [1,7]. For systemic transport, phloem mobility of the nutrient or molecule determines whether foliar application will correct deficiencies in sink tissues.

Practical recommendations for researchers and practitioners

- Integration, not replacement: Use foliar sprays as supplements to soil fertilization. Targeted foliar treatments excel at correcting acute micronutrient deficiencies and supporting critical phenological stages (e.g., pre-flower, early grain fill). Pilot side-by-side trials are recommended to quantify added value under local conditions [1,3].

- Formulation and compatibility: Select chelated micronutrients or low-molecular alternatives for improved mobility; test compatibility when tank-mixing bio stimulants, pesticides, or adjuvants to avoid antagonism or precipitation [7].

- Timing and environment: Apply when stomata are favorably open (early morning or late afternoon, depending on crop), with attention to low wind and moderate humidity to prevent rapid droplet evaporation and drift [7].

- Dose response and phytotoxicity: Conduct small-scale phytotoxicity tests across representative genotypes and developmental stages before field-scale use; follow manufacturer guidance for concentrations, especially with engineered nano-materials [2].

- Monitoring and decision support: Integrate remote sensing indices (e.g., NDVI, PRI) and leaf tissue testing to guide timing and quantify responses post-application [5].

Environmental, Safety, and Regulatory Considerations

While foliar application can reduce the absolute quantity of nutrient applied and lower off-target losses relative to some soil applications, novel formulations, especially nanoparticles, raise questions about persistence in the phyllosphere, wash-off into soils and water, non-target organism exposure, and possible trophic transfer. Agencies and researchers recommend: transparent ecotoxicological datasets, standard testing methods for nano-materials, buffer zones and worker protection standards during aerial or UAV spraying, and lifecycle assessments as part of commercialization plans [4,8,9].

Knowledge Gaps and Research Priorities

- Standardized, multi-site trials: Harmonized field trials across contrasting agroecosystems to test efficacy, environmental fate, and economic viability.

- Mechanisms at crop and cellular levels: More studies linking molecular mode of action (signal transduction, transporter engagement) with field-scale outcomes.

- Environmental fate of nano-carriers: Soil and aquatic fate, bioaccumulation potential, and effects on beneficial microbiomes.

- Decision support integration: Validated algorithms that translate remote sensing signals into foliar spray prescriptions with ROI metrics for growers.

Conclusion

Foliar nutrition is an increasingly important component of integrated nutrient management, offering tangible opportunities to improve nutrient use efficiency and crop resilience when combined with advances in nanotechnology, bio stimulants, and precision application tools. However, responsible adoption requires that foliar strategies complement rather than replace soil fertility programs, and that innovations especially nano-enabled formulations are accompanied by transparent ecotoxicological assessments, lifecycle analyses, and appropriate regulatory oversight. Economic analyses, demonstration trials, and targeted extension are needed to ensure benefits translate from experimental plots to farms, particularly in smallholder contexts. Finally, decision-support systems that integrate remote sensing, field diagnostics, and crop models, together with capacity building for growers and advisers, will be critical to scale foliar approaches sustainably and safely.

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