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Plant Micro and Macronutrients: Multidisciplinary and Targeted Approaches to Investigate their role in Plant Growth and Regulation

Aniruddha Acharya[1] · Yongjian Qiu[2] · Shankar Ganapathi Shanmugam[3]

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Introduction

Plants need several elements for their growth, development and cellular metabolism. Elements classified as macronutrients includes carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S), are required in larger amounts compared to micronutrients such as zinc (Zn), manganese (Mn), iron (Fe), sodium (Na), boron (B), molybdenum (Mo), chlorine (Cl) and copper (Cu) that are needed in trace amounts for plant metabolism (Nadeem et al. 2018). The sequestration, transport, accumulation and metabolic roles of these elements have been exhaustively investigated, leading to discovery of several channels, transporters and molecular switches that regulate their utilization by plants. The knowledge gained has been utilized by genetics, genomics and breeding technologies to biofortify crops and advance food and nutritional security. However, several aspects of plant growth and development in relation to plant nutrition are poorly understood. Again, the role and metabolism of elements such as silicon in plant cells remain elusive (Ma and Yamaji 2008). Exogenous and endogenous nutrient interactions, nutrient use efficiency, the role of microbes in nutrient sequestration, the cross talks between phytohormones pertaining to plant nutrition, nanofertilizers, stress resilience, and biostimulants are some of the emerging topics in the field of plant nutrition. The overarching goal of this special issue is to contextualize plant nutrition with broader perspectives of plant growth and regulation.

Plant nutrition has reemerged as an important scientific field due to several evolving areas of interest such as plant stress-resilience, heavy-metal pollution, emerging phytopathogens, soil degradation, erratic weather, micronutrient deficiency among human population, climate-smart agriculture, nutritional security, environmental sustainability, green fuel, space farming, and urban agriculture. The growing demands of food and feed compounded with abiotic stress, biotic stress and limited arable land have forced farmers to utilize marginal soil for agriculture. Underutilized plant species (orphan crops) and crop wild relatives (CWRs) are being investigated to supplement commercial crops to provide nutritious and sustainable sources of food (Chapman et al. 2022). Thus, investigating plant nutrition pertaining to plant growth and development is crucial to agricultural, environmental sustainability and sustaining human colonies beyond earth. The advent of new tools and new areas of science such as genome editing, nanobiotechnology, synthetic biology, artificial intelligence and autonomous labs have injected unprecedented pace and precision of discovery. A multidisciplinary and targeted approach is essential to integrate these emerging technologies and understand the mechanistic basis of plant nutrients in plant growth and development. Macronutrients and micronutrients being fundamental to the structure and function of plant cells, this special issue will initiate discussions among the scientific community and stakeholders while presenting the most recent research on the topic.

Macronutrient and Micronutrient

This special issue contains articles that illustrate recent research on micronutrients and macronutrients in plants pertaining to their growth and development. Genomic insights into their acquisition, transport and assimilation

✉ Aniruddha Acharya
aniruddha1302@gmail.com

Yongjian Qiu
yqiu@olemiss.edu

Shankar Ganapathi Shanmugam
sg383@igbb.msstate.edu

[1] Arkansas Tech University, Russellville, AR, USA

[2] University of Mississippi, Oxford, MS, USA

[3] Mississippi State University, Starkville, MS, USA

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have been discussed. Nutrient management has been discussed with special focus on biostimulants, amendments, biofertilizers and nanofertilizers. The role of nutrients in ameliorating biotic and abiotic stress has been investigated. Das & Adak reviews recent reports on the role of phytohormones, transcription factors (TFs), microRNAs, epigenetics and secondary messengers such as calcium ions and reactive oxygen species on regulation of mineral acquisition under drought stress (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-11791-8). Raigar et al. conducted meta-QTL analysis to understand the molecular mechanism of iron (Fe) and zinc (Zn) uptake in rice with a target of micronutrient biofortification. Candidate genes such as *OsNiR*, *OsFRDL1*, *OsFRO7*, *OsC3H54*, *OsEnS-6*, and *OsEnS-115* located in chromosomes 1, 3, 6, and 7 were identified as targets for marker-assisted breeding programs and nutritional improvement of rice (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-11960-9). Sameeullah investigated morphological, anatomical, physiological and molecular response of different wheat cultivars in iron-deficient soil conditions to identify iron-use efficiency. Destan variety was identified as a highly efficient variety for iron acquisition in iron-deficit conditions (https://link.springer.com/article/https://doi.org/10.1007/s00344-026-12308-7). Sarkar & Gogoi reviewed the anatomical, physiological and metabolic role of micronutrients such as molybdenum (Mo) and chlorine (Cl^-) in plants. They discussed their mechanism of uptake, transport and distribution (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-11931-0). Ferreira et al. investigated the effect of nickel (Ni) stress on the morphology and physiology of *Calopogonium mucunoides* and *Canavalia ensiformis*. Data obtained from Ni-stresses plants such as gaseous exchange, stomatal density, stomatal conductance, leaf morphology, antioxidant enzyme activity, chlorophyll concentration, water use efficiency and membrane instability suggested *Canavalia ensiformis* as a potential candidate for phytoremediation of Ni (https://link.springer.com/article/https://doi.org/10.1007/s00344-026-12250-8). A three-year field experiment by Kumar et al. evaluated the effect of micronutrients and plant growth regulators on forage sorghum. The application of micronutrients and growth regulators in appropriate amount resulted in improved nutrient profile, digestibility and harvest of forage (https://link.springer.com/article/https://doi.org/10.1007/s00344-026-12275-z). Among the articles that investigated the role of macronutrients in plant growth and regulation, Qian et al. studied the variation of macronutrients, non-structural carbohydrates and phytohormones in different floral organs and at different growth stages of *Abelmoschus Manihot*. They emphasized the significance of the study in improving nutrient management thus, optimizing cultivation practices (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-11930-1). The effects of foliar application of calcium on growth, physiology, metabolism and essential oil biosynthesis of *Ocimum basilicum* was investigated by Hajam & Bashri (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-12017-7). El-Beltagi et al. reviewed the uptake, metabolism and role of sulfur (S) in plant growth, development and stress response. They discussed sulfur nutrition in the perspective of agriculture, crop resilience and food security (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-12030-w). The effect of phytic acid reduction in germination, vigor and biochemical properties of maize seeds was investigated by Rojaria et al. They used single and double mutant maize inbreds along with their wild-type parent and evaluated the effect on field conditions. They reported no significant adverse effects of reduced phytic acid on seed vigor and germination (https://link.springer.com/article/https://doi.org/10.1007/s00344-026-12268-y).

Nutrient Management

Several articles in the special issue focused on nutrient management including biostimulants, amendments, biofertilizers and nanofertilizers. Sharma et al. evaluated the efficacy of Integrated nutrient management (INM) in improving soil health, crop yield and enhancing nutrient profile of crops grown in acidic soil. *Vigna unguiculata* was used as a candidate and physiological performances were recorded to estimate the effect of INM. The results indicated INM as a robust strategy to improve soil health and advance sustainable agriculture (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-11964-5). A meta-analysis study by Perez et al. assessed the effect of soil amendments such as manure, sewage sludge, biochar, lime, peat moss and compost on metal accumulation in plants. The role of pH and exposure time were also analyzed. The reported high variability of metal accumulation on plants with a consensus that amendments generally reduced overall metal accumulation in plants (https://link.springer.com/article/https://doi.org/10.1007/s00344-026-12095-1). Application of humic acid and seaweed extract improved macronutrient and micronutrient levels in custard apple leaves. The study by Yadav et al. reported that besides mineral content improvement, physiological parameters, growth parameters and productivity improved (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-11888-0). Ahmed et al. evaluated the role of organic and inorganic amendments such as biochar, compost, bio-gypsum, gypsum, and a Ca waste by-product on nutrient use efficiency, growth and physiological performance of rice plants. Results indicated improvement on all abovementioned parameters including yield thus, confirming the role of amendments on sustainable rice farming practices (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-11900-7). Kailasam et al. utilized the phosphate solubilizing bacteria *Cronobacter muytjensii* from coral reef environment to enhance the growth of rice, tomato and chilli plants in soil with high salt content. The strain produced several organic acids, enzymes and facilitated nitrogen fixation, mineral solubilization while exhibiting antagonistic activities against several fungal strains affecting plants. The authors considered the strain to be a useful candidate for biocontrol and improve phosphorous availability in saline conditions (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-11954-7). Bagnazari et al. reported the use of *Agrobacterium* sp. ER40 and *Paenibacillus peoriae* ER11 as bioelicitors to improve physiological parameters, growth parameters and enhance bioactive compound production in the plant *Zataria multiflora* Boiss (https://link.springer.com/article/https://doi.org/10.1007/s00344-026-12166-3). Reports by Shirvani-Naghani et al. confirms the beneficial effects of exogenously applied copper oxide nanoparticles (CuONPs) on drought-stressed *Glycine max* (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-11945-8). In another report, Zahedi et al. confirmed that exogenous application of $ZnTiO_3$ nanostructures on salt stressed *Ficus carica* L. improves their physiological functions by enhancing root growth, boosting antioxidant response and improving chlorophyll content (https://link.springer.com/article/https://doi.org/10.1007/s00344-026-12069-3). Khan et al. estimated the effect of manganese sulfide nanoparticles (MnS NPs) on oilseed plants such as *Eruca sativa* and *Linum usitatissimum*. They noticed improved growth of stems and roots, improved oil content and higher fruit yield of plants treated with manganese sulfide nanoparticles (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-11966-3). Bilge et al. investigated the role of silicon oxide nanoparticles (SiO_2-NPs) on drought stressed *Oryza sativa*. Physiological parameters, biochemical parameters and mineral analysis indicated a positive role of silicon oxide nanoparticles (SiO_2-NPs) in alleviating drought stress (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-11989-w). The role of calcium nanoparticles (Ca-NPs) in alleviating drought stress in *Brassica napus* was investigated by Ayyaz et al. Their study indicated physiological and metabolic shift towards adaptation to drought stress following calcium nanoparticles treatments (https://link.springer.com/article/https://doi.org/10.1007/s00344-026-12141-y).

Stress Resilience

Several articles reported on the role of macronutrient and micronutrients in managing stress in plants, thus supporting their growth and development under unfavorable conditions. Chauhan et al. showed that application of nano-micronutrients and macronutrients alleviated drought stress in wheat as indicated by their physiological and metabolic profile (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-12042-6). Chakraborty et al. found that micronutrient boron mitigates the effect of heat stress in the early stages of development of wheat plants. Physiological, enzymatic and morphological comparison established the use of boron as a low-cost agronomic strategy to improve wheat production under heat stress (https://link.springer.com/article/https://doi.org/10.1007/s00344-026-12161-8). Alinia et al. reported the ameliorative effects of silicon and melatonin on salt stressed *Cyamopsis Tetragonoloba* L., they observed significant improvement in morphological, physiological, biochemical and nutritional attributes of the plant under slat stress when melatonin and silicon were applied in combination (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-12046-2). In a report by Kwon et al., heat stressed soybean plants benefitted from foliar application of macronutrients, micronutrients and organic acids. Comprehensive changes in metabolic profiles including secondary metabolites were noted (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-12014-w). Ansari et al. investigated the role of growth regulators such as melatonin and salicylic acid in reducing Arsenic (As) toxicity on *Cucumis melo*. Melatonin and salicylic acid alleviated arsenic stress by improving photosynthetic potential, reducing oxidative stress and modulating gene expression that benefitted the plants stressed with arsenic (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-11886-2). Finally, Javed et al. investigated the role of sulfur application on *Brassica napus* and their protective role against specialist herbivore *Brevicoryne brassicae* (https://link.springer.com/article/https://doi.org/10.1007/s00344-025-11884-4).

Final Remarks

Plant nutrients are fundamental to the growth and development of plants. Many of their structural, functional and regulatory roles have been identified. However, the complexity of biological systems makes it challenging to understand the networks and interactions between nutrients and environment. The physical, chemical and biological factors that regulate the uptake and utilization of nutrients are of significant interest in agriculture, environment and space biology. Plants are fundamental to the existence of humans thus understanding the role of nutrients in plant growth and development is of extreme importance. Emerging technologies such as artificial intelligence, autonomous labs and synthetic biology hold great promise in accelerating research with precision (Zhang et al. 2025). Thus, the future direction of research on plant growth and regulation will involve the integration of these technologies with existing technologies such as CRISPR gene editing and bioinformatics. We hope this special issue will be very useful for plant scientists and will initiate discussions in academia, industry and among stakeholders.

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Declarations

Conflict of Interest The authors declare that there is no conflict of interests.

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